NASA/TM-2004-212850

Hypothetical Reentry Thermostructural Performance of Space Shuttle Orbiter With Missing or Eroded Thermal Protection Tiles

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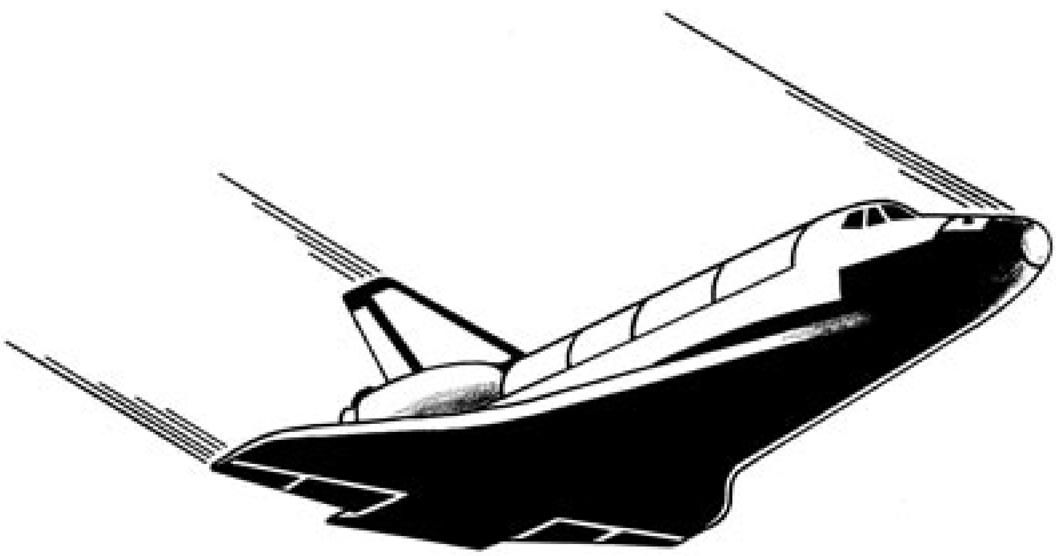

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July 2004

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ABSTRACT

This report deals with hypothetical reentry thermostructural performance of the Space Shuttle orbiter with missing or eroded thermal protection system (TPS) tiles. The original STS-5 heating (normal transition at 1100 sec) and the modified STS-5 heating (premature transition at 800 sec) were used as reentry heat inputs. The TPS missing or eroded site is assumed to be located at the center or corner (spar-rib juncture) of the lower surface of wing midspan bay 3. For cases of missing TPS tiles, under the original STS-5 heating, the orbiter can afford to lose only one TPS tile at the center or two TPS tiles at the corner (spar-rib juncture) of the lower surface of wing midspan bay 3. Under modified STS-5 heating, the orbiter cannot afford to lose even one TPS tile at the center or at the corner of the lower surface of wing midspan bay 3. For cases of eroded TPS tiles, the aluminum skin temperature rises relatively slowly with the decreasing thickness of the eroded central or corner TPS tile until most of the TPS tile is eroded away, and then increases exponentially toward the missing tile case.

NOMENCLATURE

Al	aluminum
C41	four nodes convection element
F_{ij}	radiation exchange view factor
h	thickness of eroded TPS tile, in.
h_o	thickness of intact TPS tile, in.
JLOC	joint location (node or grid point)
K21	two nodes conduction element
K41	four nodes conduction element
K81	eight nodes conduction element
M	Mach number
R41	four nodes radiation element
RTV	room temperature vulcanized
SIP	strain isolation pad
SPAR	Structural Performance and Resizing (finite-element computer program)
STS-1	space transportation system-1
STS-5	space transportation system-5
t	time counted from the start of reentry, sec
T	temperature, °F
TPATH	NASA Dryden theoretical thin skin aerodynamic heating computer program
TPS	thermal protection system

INTRODUCTION

During the final construction stage of the Space Shuttle orbiter *Columbia* (1980), the authors of this report spent extensive time at Rockwell International at Downey, California gathering dimensional data from blueprints of the *Columbia* wings and fuselage structures. Those dimensional data were needed for the preflight reentry heat transfer and thermal stress analyses of the orbiter *Columbia*. Before the *Columbia* maiden flight, space transportation system-1 (STS-1), quite a few finite-element and finite-difference thermal models were generated for the orbiter structures for extensive preflight reentry heat transfer analysis (refs. 1–19). At that time (1980), NASA Langley Research Center (Langley, Virginia) had developed a new finite-element computer code called Structural Performance and Resizing (SPAR) (ref. 20). By using the SPAR program, the finite-element thermal models could be converted easily to finite-element structural models for thermal stress analysis using the same nodal coordinates (the nodal locations of the finite-difference thermal models are not coincidental with those of the corresponding finite-element structural models).

The early major thermal and structural models included three cross sections of the orbiter wing [WS134 (contains wheel well and landing gear), WS240, and WS328], one midfuselage cross section (FS877), and a complete orbiter wing (WING). Also, several small thermal models were generated for the studies of internal radiation from nonsmooth hat-stiffened wing panel surfaces.

Using the designed reentry flight trajectory, the preflight structural temperatures were calculated. These temperatures later compared fairly well with the maiden flight (STS-1) data of the orbiter. For subsequent flights, from STS-2 through STS-5, the calculated structural temperatures also compared fairly well with the flight data. The results of all of the past extensive thermostructural analyses were published earlier in references 1 through 19.

After STS-5, five additional finite-element models (Model A, Model B, Model C, Model D, and Model E) with different element densities were generated for bay 3 of WS240. Those models were used for extensive studies of the effect of the element density on the accuracy of finite-element solutions calculated from the then newly developed SPAR finite-element computer program (refs. 11, 12, 15, 16, and 18). Bay 3 of WS240 was chosen because bay 3 was the most heavily instrumented bay and provided ample flight-measured temperature data at various structural locations for comparison with the calculated nodal temperatures.

In the early thermostructural studies, the main focus was to estimate the structural temperatures and the associated thermal stresses induced in the orbiter *Columbia* with intact thermal protection system (TPS) tiles before its maiden flight, STS-1. Also, before STS-1, the thermal buckling problems of the wing skin panels were investigated for a hypothetical case in which one TPS tile was assumed missing during the aerodynamic cooling phase following the heating phase (ref. 8). In these earlier studies, hypothetical cases of the orbiter with missing or eroded TPS tiles during the reentry heating phase were not considered because they were low priority items.

The loss of *Columbia* was a great shock to the authors because of past close research ties generated between the researchers and *Columbia* before its maiden flight, STS-1, and during the subsequent flights STS-2 through STS-5. The loss strongly motivated the authors to look into hitherto unexplored areas of hypothetical reentry thermostructural performances of the orbiter structures, assuming one or more TPS tiles are either missing or eroded down to a less protective thickness.

This report presents the results of the hypothetical reentry heat transfer analyses of the orbiter wing structure with missing or eroded TPS tiles. Additionally, this report shows how high the aluminum skin temperatures can rise at the TPS tiles missing or eroded sites.

EXISTING THERMAL MODEL

The five finite-element thermal models (Model A, Model B, Model C, Model D, and Model E) (refs. 11, 12, 15, 16, and 18) generated earlier for bay 3 of the orbiter wing midspan cross section (fig. 1) are three-dimensional models with different element densities. Model A is composed of the coarsest elements and Model E is composed of the finest elements. Model C (fig. 2) is of moderate element density, does not require excess computation time, and could provide fairly accurate solutions; therefore, Model C was chosen for the present hypothetical reentry heat transfer analysis of the orbiter wing with missing or eroded TPS tiles. Table 1 lists the size of Model C.

Table 1. Size of Model C SPAR thermal model.

Number	Item
636	joint locations, JLOC (nodes)
82	two nodes conduction elements, K21
232	four nodes conduction elements, K41
336	eight nodes conduction elements, K81
137	four nodes radiation elements, R41
88	four nodes convection elements, C41
6,894	radiation view factors, F_{ij}

Model C considers all modes of heat transfer processes: conduction, internal radiation, external radiation, and internal convection. The 6,894 view factors F_{ij} (table 1) are to be calculated internally by the SPAR program. For the analysis of each case of missing or eroded TPS tiles, Model C (fig. 2) had to be slightly modified by changing the nodal locations to create the TPS tiles missing or eroded site.

MISSING TPS TILES ANALYSIS

For the missing TPS tiles analysis, the TPS tiles missing sites were at two locations (location 1 and location 2). Location 1 is the central region of the windward surface of the thermal model. Cases analyzed for location 1 included one, two, three, and four TPS tiles missing. Figures 3(a) through (d) show the four modified thermal models generated from Model C (fig. 2) for the preceding four cases.

Location 2 is the corner (spar-rib juncture) of the windward surface of the thermal model. Cases analyzed for location 2 included one, two, four, and six TPS tiles missing. Figures 4(a) through (d) show the modified thermal models generated from Model C for those four cases. Because the total area of the corner TPS tiles missing site is equally shared by four adjacent bays, only one-quarter of the total area of the TPS tiles missing site was used in the thermal model for location 2 cases.

ERODED TPS TILES ANALYSIS

For the eroded TPS tiles analysis for both location 1 and location 2, the eroded TPS thicknesses, h, considered were $h/h_o = 1$ (intact), 3/4, 1/2, 1/4, 1/8, 1/16, 0 (missing tiles case) of the original intact TPS thickness h_o.

For location 1, only one central TPS tile was eroded at the windward panel center of the thermal model. Figure 5 shows a typical eroded thermal model with the central TPS tile eroded by 50 percent. Notice that in the eroded thermal model, the neighboring TPS thickness is tapered down to the eroded site of thickness h.

For location 2, one TPS tile was also eroded at the windward panel corner (spar-rib juncture). Figure 6 shows a typical eroded thermal model with corner TPS tile eroded by 50 percent. Again, the neighboring TPS thickness was tapered down to match the eroded thickness h.

AERODYNAMIC HEATING

For heat input, two types of reentry aerodynamic heating rates (STS-5 and modified STS-5 heating) were used.

STS-5 Heating

The first type of heating is STS-5 heating. This is the original STS-5 reentry heating of the Space Shuttle orbiter *Columbia* with normal transition (from laminar heating to turbulent heating) at t = 1100 sec from reentry. Based on the STS-5 reentry trajectory shown in figure 7, the STS-5 heating rates (setting transition time at t = 1100 sec) were calculated in 1980 (ref. 1) for different surface stations of the orbiter. Figure 8 shows the previously calculated STS-5 heating rates at typical stations of the lower and upper surfaces of the orbiter wing midspan bay 3. The heating rates for midspan bay 3 were assumed to be constant in the spanwise direction, but varying in the chordwise direction. The appendix briefly describes methods of reentry heating calculations for the benefit of readers. STS-5 heating was first used for the missing TPS tiles analysis (before the new transition time was determined for modified STS-5 heating described below) and was not used for the eroded TPS tiles analysis.

Modified STS-5 Heating

The second type of heating is modified STS-5 heating. This is the original STS-5 heating, but with premature transition time at t = 800 sec to account for surface roughness created by the missing or eroded TPS tiles on the airflow. Figure 9 shows the modified STS-5 heating rates for orbiter wing midspan bay 3. The original STS-5 heating curves (fig. 8) are also plotted for comparison. Again, the STS-5 reentry trajectory shown in figure 7 was used in the modified STS-5 heating calculations by retarding the transition time to t = 800 sec. Notice from figure 9 that by retarding the transition time from t = 1100 sec to t = 800 sec, the peak heating rate for the lower surface increased by nearly a factor of four.

The normal transition (from laminar heating to turbulent heating) for the Space Shuttle orbiter flights occurs at about t = 1100–1160 sec (fig. 7) from reentry, and is at an altitude of 160,000 ft and a velocity of approximately 10,000 ft/sec (M = 9.1). This is the time of transition as obtained from the flight data of STS-1 through STS-5.

During design of the Space Shuttle orbiter *Columbia*, Rockwell International predicted transition at approximately t = 1100 sec for a smooth surface. For the design calculations, Rockwell assumed a roughness of 0.1 in. and predicted transition at about t = 800 sec. It seems reasonable that with the loss or erosion of one or more TPS tiles, a roughness of 0.1 in. would be appropriate (since the tiles are 1.5- to 2.5-in. thick). Therefore, the preceding is the criterion for modified STS-5 heating used for the hypothetical reentry thermal analysis of the orbiter wing with missing or eroded TPS tiles. Notice that this transition time at t = 800 sec (fig. 7) is at an altitude of 210,000 ft and a velocity of approximately 19,000 ft/sec (M = 18.5) and is slightly earlier than the time t = 934 sec (M = 18) when *Columbia* was lost. Modified STS-5 heating was used for both missing TPS tiles and eroded TPS tiles analyses.

RESULTS

The following sections present the results of hypothetical reentry heat transfer analyses of the Space Shuttle orbiter with missing or eroded TPS tiles.

Missing TPS Tiles—STS-5 Heating

Figures 10(a) through (d) and 11(a) through (d) show aluminum skin temperature distributions at peak temperature occurrence times for different cases of missing TPS tiles at location 1 and location 2 using STS-5 heating (transition at t = 1100 sec). Furthermore, figures 10 and 11 indicate the peak aluminum skin temperature at the center of each TPS tiles missing site and the peak room temperature vulcanized (RTV) temperature at the boundary of each TPS tiles missing site. For location 1 (fig. 10), the peak temperature zone for each case is practically pinnacle-shaped at the panel center for the present element density. For location 2 (fig. 11), the temperature distribution at the TPS tiles missing site is more moderate for each case analyzed.

Figures 12 through 15 show the time histories of strain isolation pad (SIP) temperatures and the aluminum skin temperatures for different cases of missing TPS tiles at location 1 using STS-5 heating. For location 1, the aluminum skin temperature is located at the central point of the TPS tiles missing site. In each of figures 12 through 15, the peak values of aluminum skin temperatures are indicated. The SIP at the central TPS tiles missing site burned up at 190 sec, assuming the SIP burnup point is 1000 °F. In each of figures 12 through 15, two curves of aluminum skin temperatures at the TPS tiles missing site were plotted with peak values indicated. The first curve (dashed) in figures 12 through 15 is associated with no SIP protection from the beginning of reentry, and the second curve (solid) is associated with SIP protection until burnup time. After SIP burnup, the two curves align almost on top of each other. Notice that short period of SIP protection has negligible effect on subsequent aluminum skin temperatures.

For location 1, the aluminum skin temperature reached the melting point when four TPS tiles were lost (fig. 15). Keep in mind that based on the aluminum skin temperature, reaching the melting point is not the only criterion for destruction. The other criterion is based on the RTV limit temperature above which the RTV will lose its bonding function, causing TPS tiles at the boundary of the TPS tiles missing site to fly off. This will be discussed later in this report.

In figures 12 through 15, the aluminum skin temperature curve for the intact TPS case labeled “TPS intact” is plotted for comparison. Also, the aluminum skin temperature curve labeled “SIP intact, hypothetical” is for a hypothetical SIP that was assumed to survive the reentry heating. Keep in mind that the SIP is a good insulator; and if such a hypothetical SIP could be found, it could lower the peak aluminum skin temperature for each case down to almost one-half even when the SIP is only 0.16-in. thick.

Figures 16 through 19 show time histories of the SIP temperatures and the aluminum skin temperatures at location 2 for different cases of missing corner TPS tiles using STS-5 heating. For location 2, the aluminum skin temperature is at the spar-rib juncture, which is the central point of the corner TPS tiles missing site. The peak values of aluminum skin temperatures are indicated in figures 16 through 19. The SIP at the corner TPS tiles missing site burned up at 200 sec, thus surviving by 10 sec more than the location 1 cases, as a result of corner heat sink. For the same number of missing TPS tiles, the peak aluminum skin temperature for location 2 is much lower than that for location 1, also as a result of corner heat sink (figs. 12 and 16). For location 2, the peak aluminum skin temperatures stayed below the melting point up to a case of six missing TPS tiles (fig. 19), as a result of the heat sink effect of the spar-rib juncture.

Like the location 1 cases, in figures 16 through 19, the aluminum skin temperature curve for the intact TPS case labeled “TPS intact” and the aluminum skin temperature curve labeled “SIP intact, hypothetical” were plotted for comparison. As mentioned earlier, the hypothetical (or fictitious) SIP is assumed to survive the reentry heating without burning up. Notice that the 1.6-in. thickness can provide good thermal protection because it is a super insulator.

Tables 2 and 3, respectively, summarize the key data resulting from the missing TPS tiles analysis, using STS-5 heating (transition at t = 1100 sec), for location 1 and location 2.

Table 2. Location 1 missing TPS tiles (STS-5 heating with transition at t = 1100 sec).

Missing central TPS tiles	SIP burnup time t, sec	Al skin		TPS tiles missing site boundary RTV temp. T, °F
		Peak temp. T, °F	Occurrence t, sec	
0 (intact)	none	123	1,900	123
1	190	808	1,200	504
2	190	1,075	600	710**
3	190	1,158	600	829**
4	190	1,220* (1,300)	450* (550)	754** (908)**

* Reached aluminum melting point of 1220 °F at 450 sec.

( ) Assumed no melting.

** Exceeded RTV breakdown point of 650 °F.

Table 3. Location 2 missing TPS tiles (STS-5 heating with transition at t = 1100 sec).

Missing corner TPS tiles	SIP burnup time t, sec	Al skin		TPS tiles missing site boundary RTV temp. T, °F
		Peak temp. T, °F	Occurrence t, sec	
0 (intact)	none	72	2,000	72
1	200	384	1,250	387
2	200	598	1,250	589
4	200	882	900	815**
6	200	1,027	900	958**

** Exceeded RTV breakdown point of 650 °F.

Notice from tables 2 and 3 that under the same number of missing TPS tiles, for the location 2 cases (table 3), the aluminum skin temperatures are considerably lower than the location 1 cases (table 2) because of the heat sink effect of the spar-rib juncture. For the case with one missing central TPS tile (location 1, table 2), the windward aluminum skin temperature at the center of the TPS tiles missing site reached a maximum of 808 °F, which exceeded the operating limit temperature of 350 °F, but was still below the melting point of 1220 °F. At the same time, at the boundary of the one central TPS tile missing site, the peak RTV temperature reached only 504 °F, which is still below the RTV breakdown point of 650 °F (above which RTV loses its bonding capability). Thus, it appears that midspan bay 3 of the orbiter wing could survive STS-5 reentry heating with one missing central TPS tile (table 2).

For the case of two missing central TPS tiles (location 1, table 2), the aluminum skin temperature reached 1075 °F, which is slightly lower than the melting point of 1220 °F; however, the RTV temperature at the boundary of the two central TPS tiles missing site reached 710 °F, which exceeded the RTV breakdown point of 650 °F. This implies that the RTV has lost its bonding capability and that the intact TPS tiles surrounding the TPS tiles missing site could be blown off, creating a larger area of TPS tiles missing site. This could cause the aluminum skin temperatures to rise and reach the melting point very quickly. Thus, upon losing two or more central TPS tiles (fig. 20, table 2), there could be no chance for midspan bay 3 of the orbiter wing to survive STS-5 reentry heating.

If the TPS tiles missing site is at location 2 (table 3), where the spar-rib juncture functions as a heat sink to quench the aluminum skin, the orbiter could survive STS-5 reentry heating with a maximum of two missing TPS tiles (table 3).

Figures 20 and 21 show the plots of peak aluminum skin temperatures and RTV temperatures (taken from tables 2 and 3) as functions of the number of missing TPS tiles, respectively, for location 1 and location 2. The peak aluminum skin temperature curves for an intact hypothetical SIP are also shown for comparison. Figures 20 and 21 are the graphical way to show the limit number of TPS tiles the orbiter wing can afford to lose at midspan bay 3 and still survive STS-5 reentry heating.

Missing TPS Tiles—Modified STS-5 Heating

Figures 22 and 23(a) and (b) show windward aluminum skin temperature distributions at peak temperature occurrence times for different cases of missing TPS tiles at location 1 and location 2 using modified STS-5 heating (transition at t = 800 sec). Furthermore, figures 22 and 23 indicate the peak aluminum skin temperature at the center of each TPS tiles missing site and the peak RTV temperature at the boundary of each TPS tiles missing site. For location 1, the peak temperature point is located at the sharp tip of the pinnacle-shaped temperature profile (fig. 22). For location 2 (fig. 23), the temperature profile at the TPS tiles missing site is roof-shaped for each case analyzed.

Figure 24 shows the time histories of windward SIP and aluminum skin temperatures at one central TPS tile missing site associated with modified STS-5 heating. Notice that the SIP at the central TPS tile missing site burned up at 190 sec. The aluminum skin temperature for location 1 is indicated at the center of the TPS tiles missing site. Also, in figure 24, two curves of aluminum skin temperatures at the TPS tiles missing site were plotted with peak values indicated. The first curve (dashed) is associated with no SIP protection from the beginning of reentry, and the second curve (solid) is associated with SIP protection until burnup time. After SIP burnup, the two curves align almost on top of each other, forming a single curve. For location 1, the aluminum skin temperature at the TPS tile missing site reached the melting point T = 1220 °F at 840 sec when only one TPS tile is lost (fig. 24). The short period of SIP protection has a negligible effect on subsequent aluminum skin temperatures. In figure 24, the aluminum skin temperature curve for the intact TPS case labeled “TPS intact” was plotted for comparison. Also, the aluminum skin temperature curve for a hypothetical SIP labeled “SIP intact, hypothetical” is assumed to survive the reentry heating. Keep in mind that the SIP is a good insulator; if such a hypothetical SIP could be found, the hypothetical SIP could drastically lower the peak aluminum skin temperature for each case even with a 0.16-in. thick layer of SIP protection. A notable observation from figure 24 is that, unlike the heating curve for the lower surface (the peak modified STS-5 heating rate is nearly four times the peak STS-5 heating rate, fig. 9), the TPS tiles missing site aluminum skin temperature induced by modified STS-5 heating only increased by nearly a factor of two of that induced by STS-5 heating because of increased radiation to the atmosphere and increased conduction of heat from the TPS tiles missing site through aluminum skin toward the cooler surrounding structures (compare figures 12 and 24).

Figures 25 and 26 show the time histories of windward SIP and aluminum skin temperatures at location 2 with one and two missing corner TPS tiles based on modified STS-5 heating. For location 2, the aluminum skin temperature was taken at the panel corner (spar-rib juncture) of the TPS tiles missing site. For location 2 (fig. 25), the SIP at the TPS tiles missing site burned up at $t = 200$ sec, which is 10 sec later than $t = 190$ sec for the location 1 case (fig. 24). The aluminum skin temperature for one corner TPS tile missing case (fig. 25) reached only $T = 814$ °F at $t = 1000$ sec. But, for the case of two missing corner TPS tiles (fig. 26), the aluminum skin temperature exceeded the melting point $T = 1220$ °F for a short duration of 80 sec.

The dashed aluminum temperature curve in each of figures 25 and 26 is associated with the case without SIP protection from the beginning of reentry, and the solid curve is associated with the case with SIP protection until burnup time. After SIP burnup, the two curves collapsed into a single curve. Again, the short period of SIP protection has a negligible effect on subsequent aluminum skin temperatures. In each of figures 25 and 26, the aluminum skin temperature curve for the intact TPS tiles case labeled "TPS intact" is plotted for comparison. Also, the aluminum skin temperature curves for intact hypothetical SIP labeled "SIP intact, hypothetical" are plotted to show that even the 0.16-in. thick intact hypothetical SIP could drastically lower the aluminum skin temperatures. Similar to location 1, modified STS-5 heating raised the windward aluminum skin temperature by nearly a factor of two (compare figs. 16, 25 and figs. 17, 26).

The key data (taken from figures 22 through 26) resulting from the missing TPS tiles analysis, using modified STS-5 heating (transition at $t = 800$ sec), are summarized in tables 4 and 5, respectively, for location 1 and location 2. Notice from table 4 that under modified STS-5 heating (transition at $t = 800$ sec), superheated air could burn through the wing skin if only a single central TPS tile is lost at location 1.

Table 4. Location 1 missing TPS tiles (modified STS-5 heating with transition at $t = 800$ sec).

Missing central TPS tiles	SIP burnup time t, sec	Al skin: Peak temp. T, °F	Al skin: Occurrence t, sec	TPS tiles missing site boundary RTV temp. T, °F
0 (intact)	none	168	1,750	168
1	190	1,220*	840	590

* Reached aluminum melting point of 1220 °F at 840 sec.

Table 5. Location 2 missing TPS tiles (modified STS-5 heating with transition at $t = 800$ sec).

Missing corner TPS tiles	SIP burnup time t, sec	Al skin: Peak temp. T, °F	Al skin: Occurrence t, sec	TPS tiles missing site boundary RTV temp. T, °F
0 (intact)	none	106	2,000	126
1	190	814	1,000	811**
2	190	1,220*	965	1,211**

* Reached aluminum melting point of 1220 °F at 965 sec.

** Exceeded RTV breakdown point of 650 °F.

At location 2 (table 5), with the loss of only one corner TPS tile, the peak aluminum skin temperature reached T = 814 °F, which is far below the melting point T = 1220 °F; however, the peak RTV temperature T = 811 °F at the boundary of the one corner TPS tile missing site exceeded the RTV operating limit temperature T = 650 °F. This implies that the RTV has lost its gripping power; therefore, the intact TPS tiles surrounding the one corner TPS tile missing site could be blown off, enlarging the missing site area and causing the aluminum skin temperature to reach the melting point. Losing two corner TPS tiles at location 2 would certainly be catastrophic.

Eroded TPS Tiles—Modified STS-5 Heating

For the eroded TPS tiles analysis, only single eroded TPS tile cases were considered for location 1 and location 2, and only modified STS-5 heating (transition at t = 800 sec) was used. Figures 27 and 28 show that variation of aluminum skin temperatures (underneath the TPS eroded site) change with the eroded thickness or different degrees of TPS-eroded thicknesses h/h_o. Notice that figures 27 and 28 also show aluminum skin temperature curves for total erosion ($h/h_o = 0$, cases of missing TPS tiles). Those curves in figures 27 and 28 were reproduced respectively from figures 24 and 25.

Tables 6 and 7, respectively, summarize the key data shown in figures 27 and 28. Note from table 6 that the orbiter wing can survive modified STS-5 heating (with transition at t = 800 sec) with one TPS tile eroded even down to 1/16 of its original thickness.

Table 6. Single central TPS eroded site (modified STS-5 heating with transition at t = 800 sec).

TPS thickness ratio, h/h_o	Al skin	
	Peak temp. T, °F	Occurrence t, sec
1 (TPS intact)	168	1,750
3/4	215	1,700
1/2	267	1,700
1/4	330	1,500
1/8	394**	1,350
1/16	458**	1,250
0 (TPS gone)	1,220*	840*

* Reached aluminum melting point T = 1220 °F at 840 sec.

** Exceeded operating temperature limit T = 350 °F.

Table 7. Single corner TPS eroded site (modified STS-5 heating with transition at t = 800 sec).

TPS thickness ratio, h/h_o	Al skin	
	Peak temp. T, °F	Occurrence t, sec
1 (TPS intact)	126	1,850
3/4	154	1,700
1/2	188	1,700
1/4	231	1,500
1/8	275	1,400
1/16	315	1,300
0 (TPS gone)	814*	1,000

* TPS tiles missing site boundary RTV temperature of 811 °F (exceeded RTV breakdown point of 650 °F).

The peak aluminum temperatures listed in tables 6 and 7 are plotted, respectively, in figures 29 and 30 as functions of TPS-eroded thickness h/h_o. Note that aluminum skin temperature rises relatively slowly with decreasing thickness of the eroded central or corner TPS until most of the TPS tile is eroded away, and then increases exponentially as the total TPS erosion (cases of missing TPS) is approached. Notice that one central TPS tile (fig. 29) and one corner TPS tile (fig. 30) may be eroded, respectively, down to as low as 20 percent and 4.5 percent of the original thickness without raising the aluminum skin temperature beyond the operating temperature limit of 350 °F.

CONCLUSIONS

Finite-element heat transfer analysis was performed on hypothetical reentry flight of the Space Shuttle orbiter with missing or eroded TPS tiles subjected to original STS-5 heating (normal transition at t = 1100 sec) and modified STS-5 heating (premature transition at t = 800 sec). The following items summarize the results.

Missing TPS Tiles—STS-5 Heating

1. Losing just one central TPS tile may not cause a catastrophic problem because the aluminum skin would not melt, the RTV would continue to maintain its bonding function, and TPS tiles at the boundary of the TPS tiles missing site would not fly off.
2. Losing two and three central TPS tiles would not melt the aluminum skin; however, the TPS tiles at the boundary of the TPS tiles missing site would fly off because the RTV is overheated and loses its bonding function.
3. Losing four central TPS tiles would melt the aluminum skin, and the TPS tiles at the boundary of the TPS tiles missing site would fly off because the RTV is overheated beyond its bonding breakdown temperature.

4. Because of the heat sink effect of the spar-rib juncture, the orbiter wing midspan bay 3 may survive the reentry heating even if it loses up to two corner TPS tiles.
5. Losing four or more corner TPS tiles would cause the TPS tiles at the boundary of the TPS tiles missing site to fly off because RTV temperatures at the boundaries of the corner TPS tiles missing sites exceed the bonding breakdown point T = 650 °F, although the aluminum skin would not melt.
6. With normal transition at t = 1100 sec, the orbiter can afford to lose only one central TPS tile or two corner TPS tiles at the lower surface of wing midspan bay 3.

Missing TPS Tiles—Modified STS-5 Heating

1. Losing one central TPS tile would cause the aluminum skin to melt and the RTV to lose its bonding strength, causing the TPS tiles surrounding the TPS tiles missing site to fly off.
2. Losing one corner TPS tile would not melt the aluminum skin; however, the TPS tiles at the boundary of the TPS tiles missing site would fly off because the RTV loses its bonding strength.
3. Losing two corner TPS tiles would cause the aluminum skin to melt and the RTV to lose its bonding strength.
4. With premature transition at t = 800 sec, the orbiter cannot afford to lose even one TPS tile at the center or at the corner of the lower surface of wing midspan bay 3.

Eroded TPS Tiles—Modified STS-5 Heating

1. Aluminum skin temperature rises relatively slowly with decreasing thickness of the eroded central or corner TPS tiles until most of the TPS tile is eroded away, and then increases exponentially toward the case of missing TPS tiles.
2. One central TPS tile may be eroded down to 20 percent of the original thickness without raising the aluminum skin temperature beyond the operating temperature limit.
3. One corner TPS tile may be eroded down to as low as 4.5 percent of the original thickness without causing the aluminum skin temperature to rise beyond the operating temperature limit.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, California
January 16, 2004

FIGURES

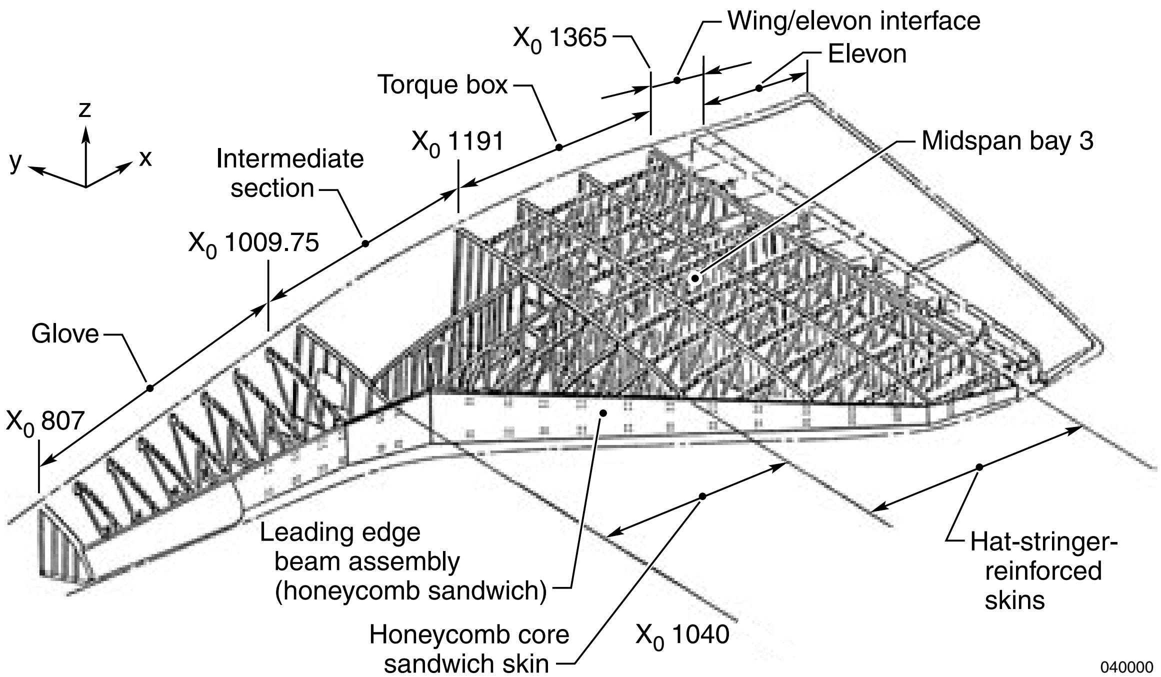


Figure 1. Location of Space Shuttle orbiter wing midspan bay 3 modeled for reentry heat transfer analysis.

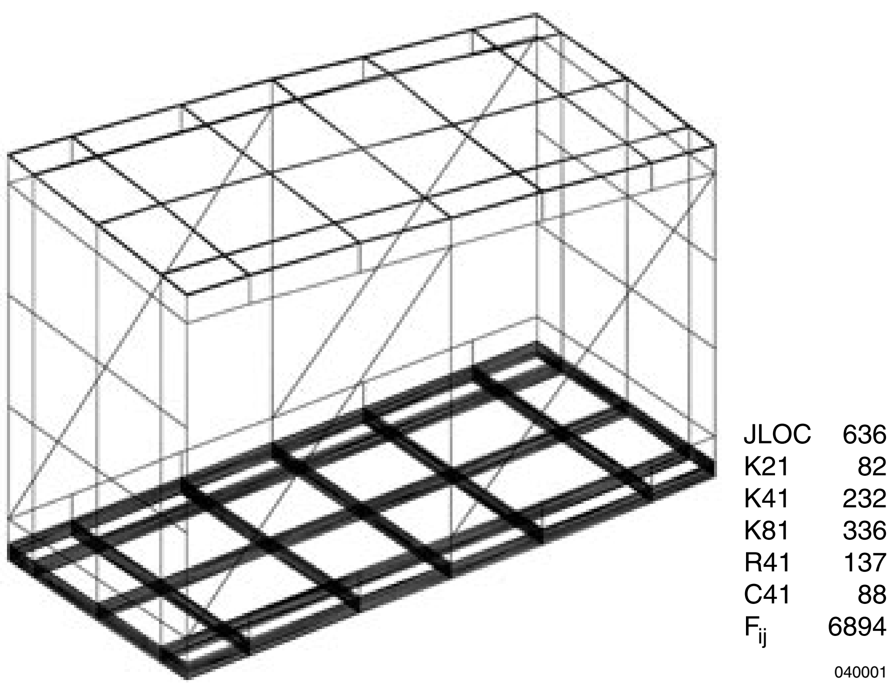
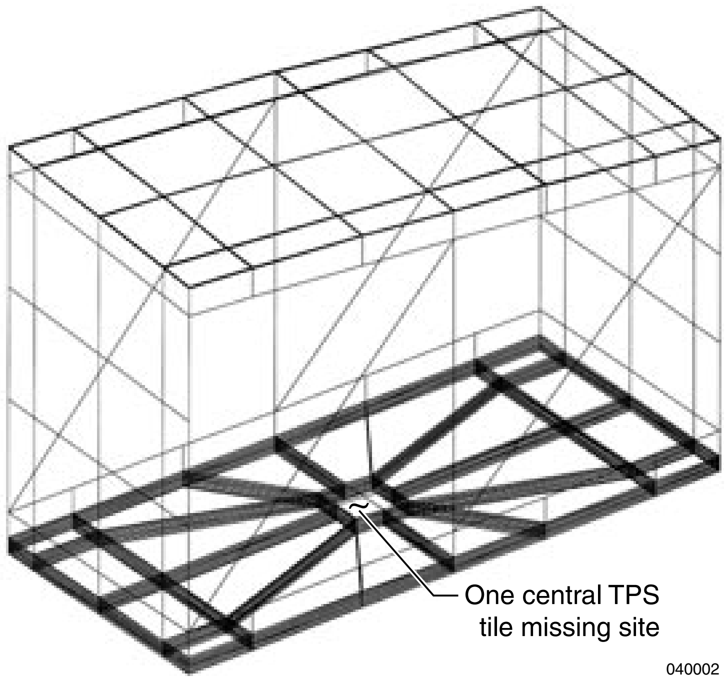
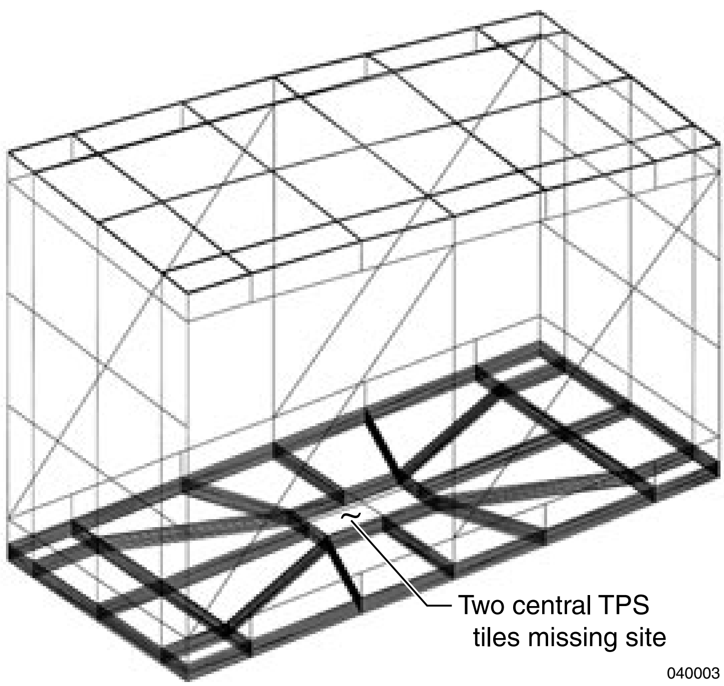


Figure 2. Original thermal model (Model C) for midspan bay 3 of orbiter wing; TPS tiles intact.

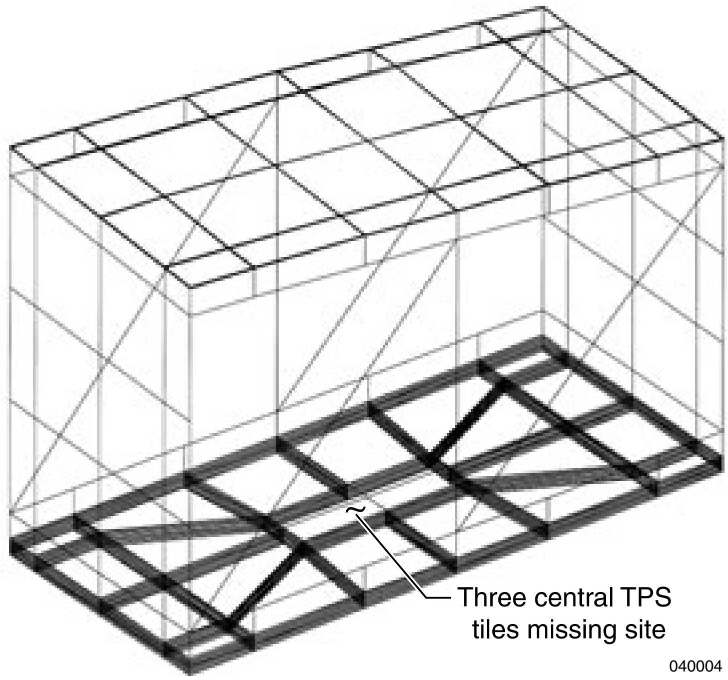


(a) One central TPS tile missing.

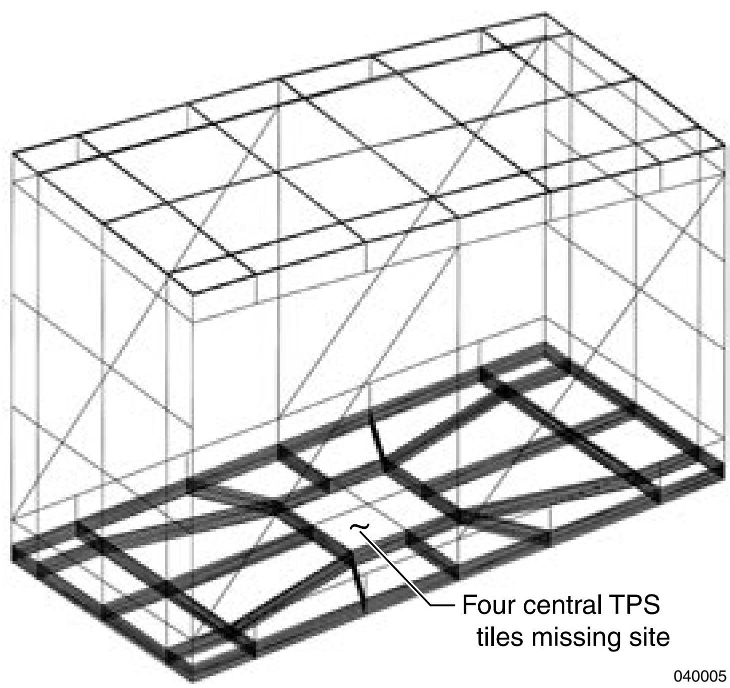


(b) Two central TPS tiles missing.

Figure 3. Modified thermal models with missing TPS tiles at central region (location 1) of windward surface.

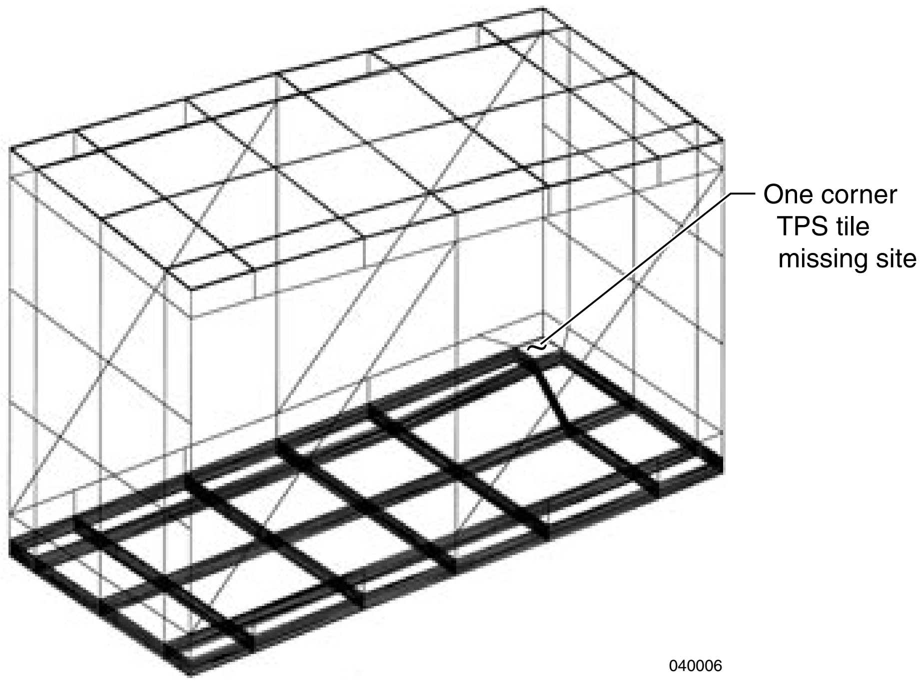


(c) Three central TPS tiles missing.

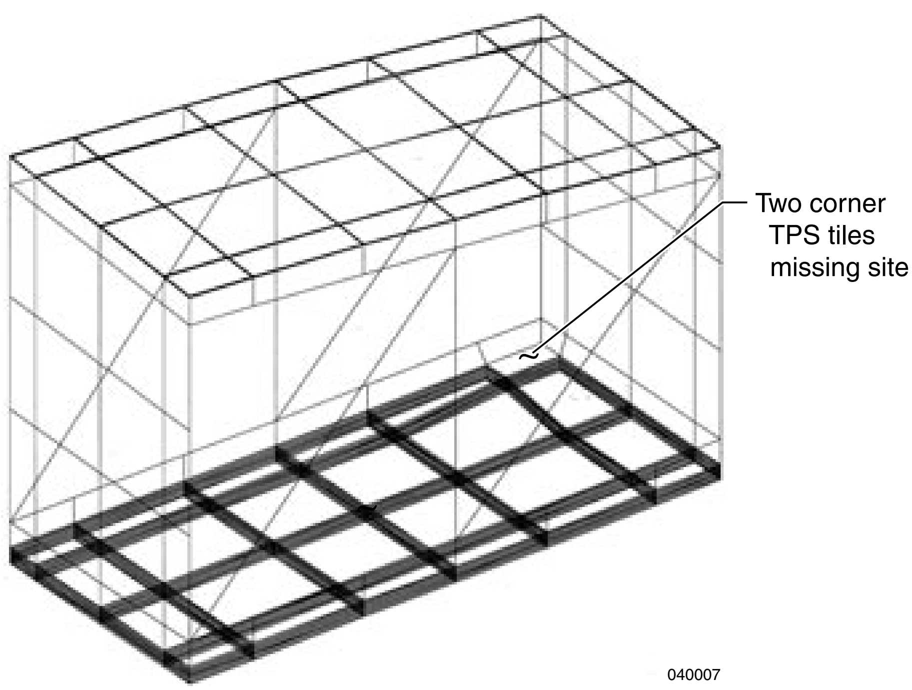


(d) Four central TPS tiles missing.

Figure 3. Concluded.

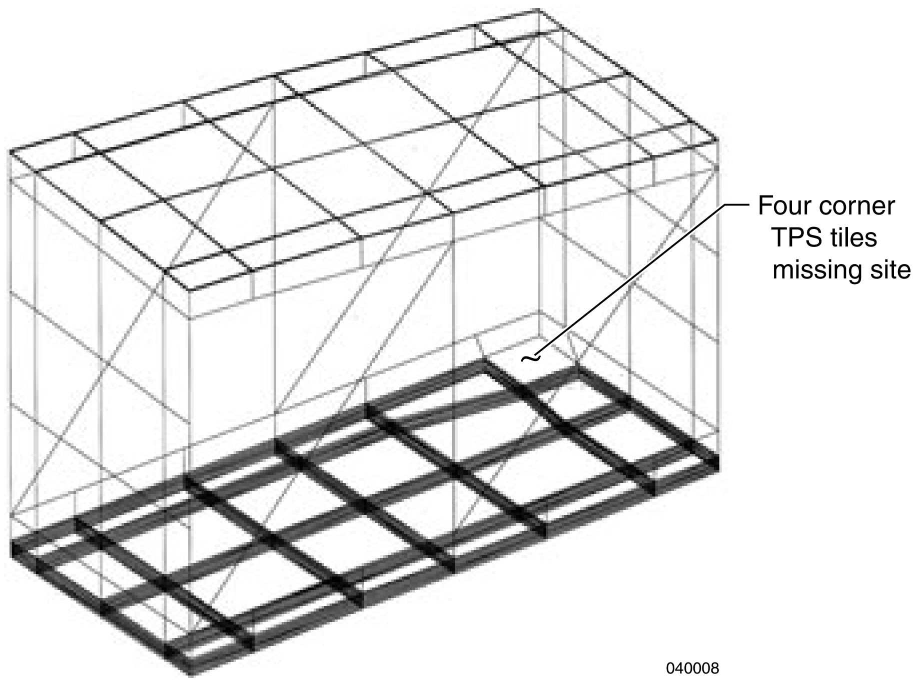


(a) One corner TPS tile missing.

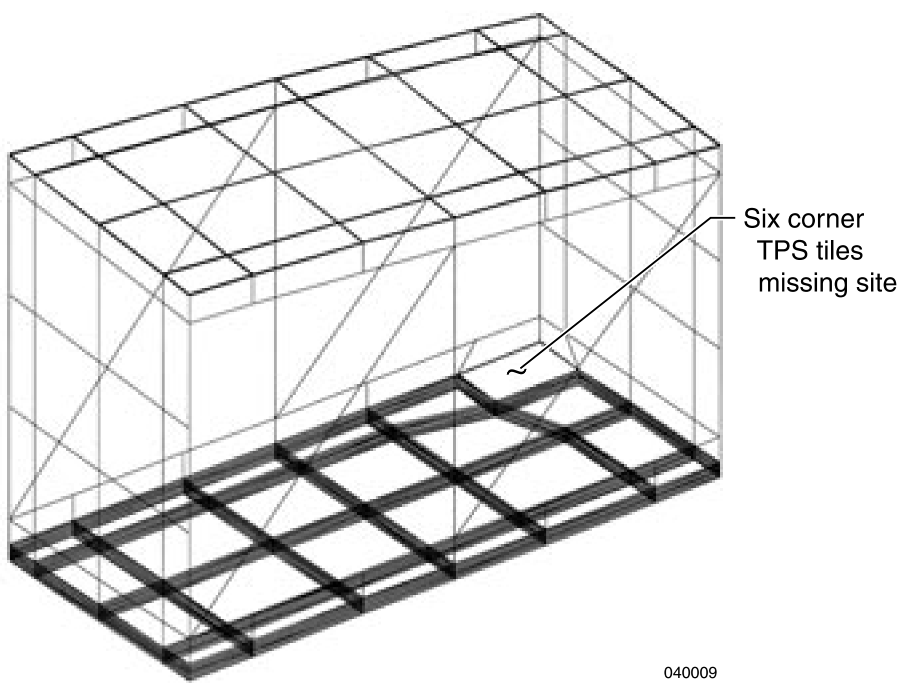


(b) Two corner TPS tiles missing.

Figure 4. Modified thermal models with missing TPS tiles at corner region (location 2) of windward surface.



(c) Four corner TPS tiles missing.



(d) Six corner TPS tiles missing.

Figure 4. Concluded.

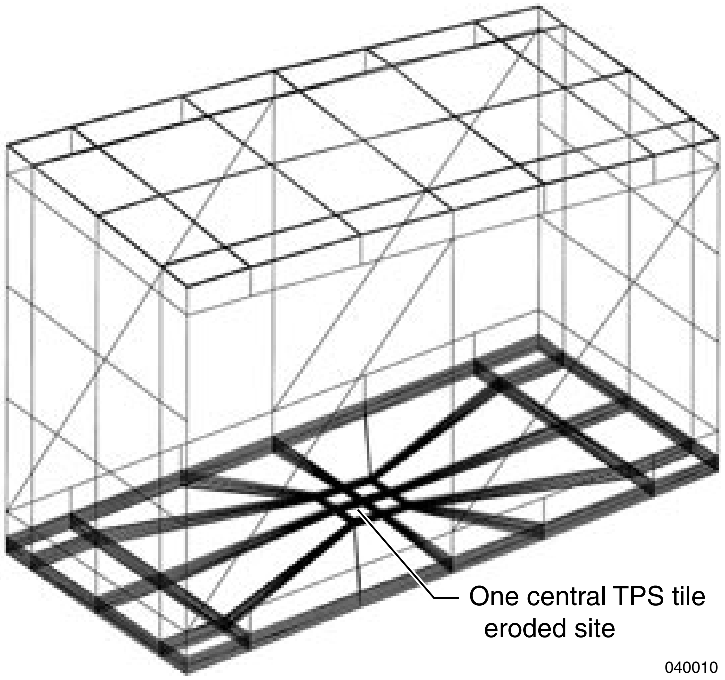


Figure 5. Modified thermal model with one eroded TPS tile at central region (location 1) of windward surface; 50 percent eroded ($h/h_o = 0.5$).

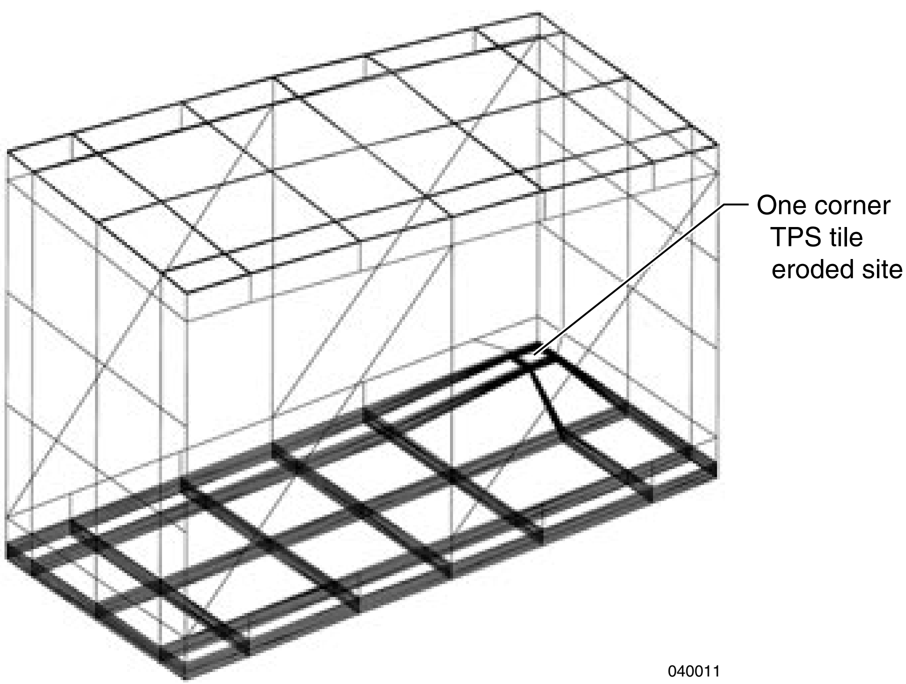


Figure 6. Modified thermal model with one eroded TPS tile at corner region (location 2) of windward surface; 50 percent eroded ($h/h_o = 0.5$).

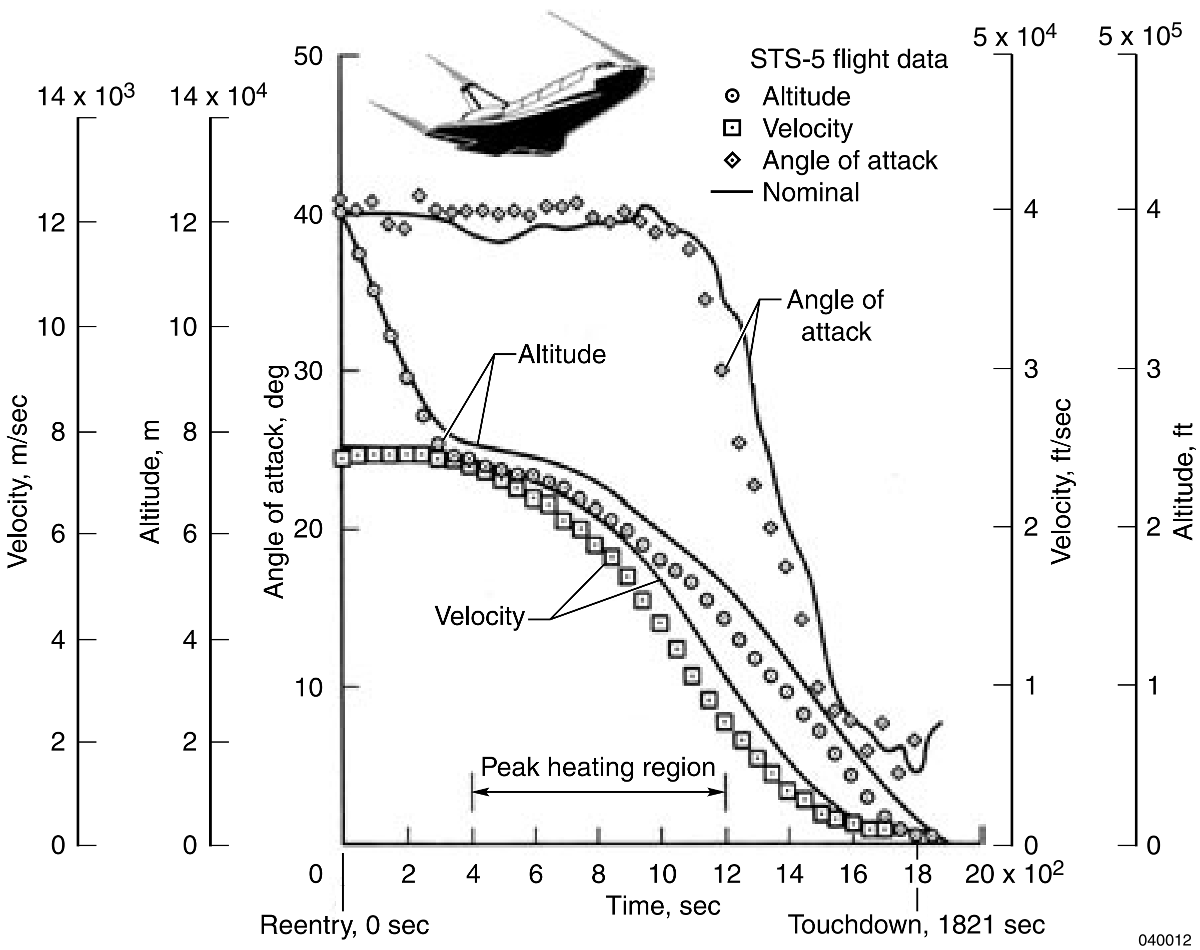


Figure 7. Reentry trajectory of STS-5.

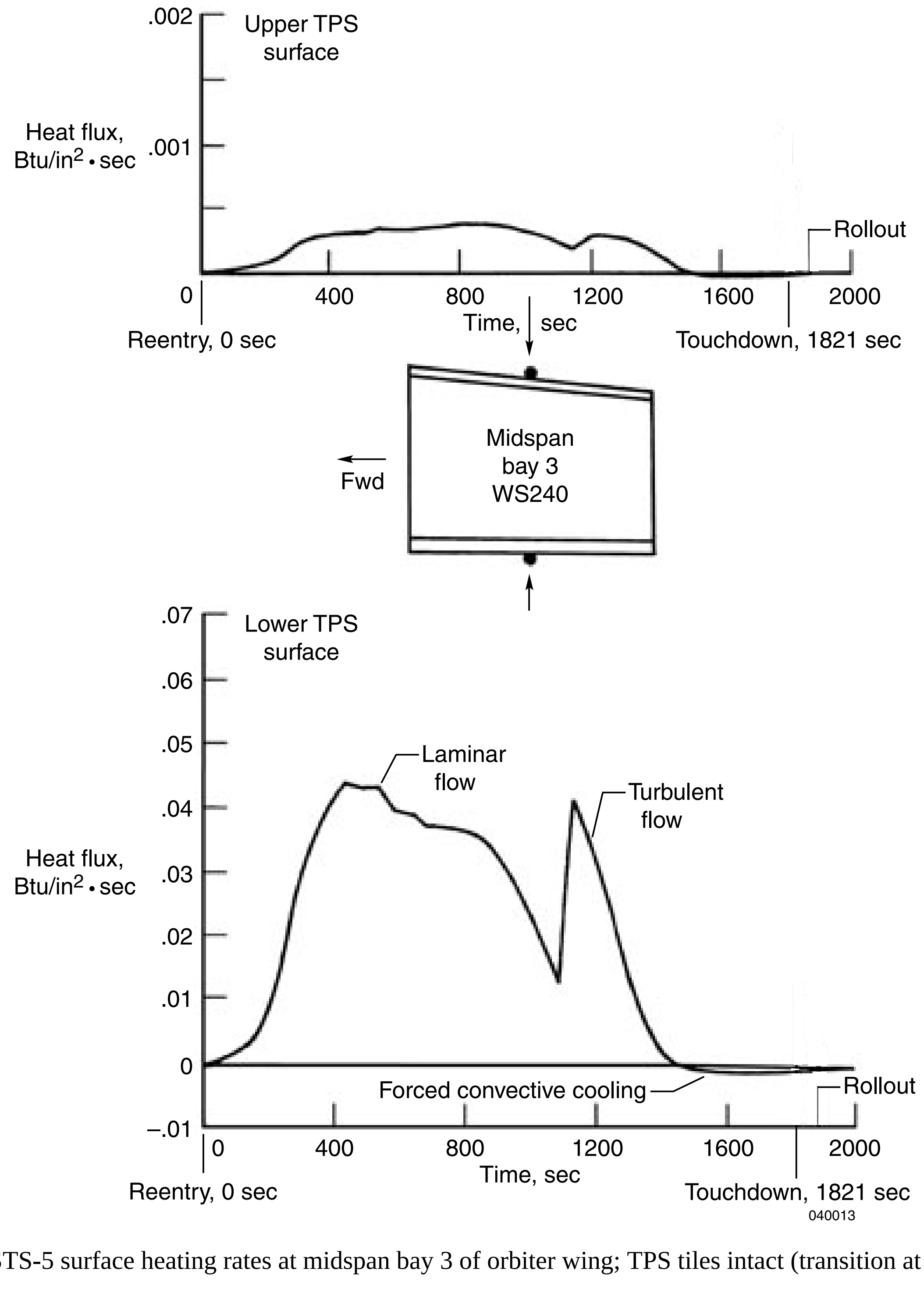


Figure 8. STS-5 surface heating rates at midspan bay 3 of orbiter wing; TPS tiles intact (transition at t = 1100 sec).

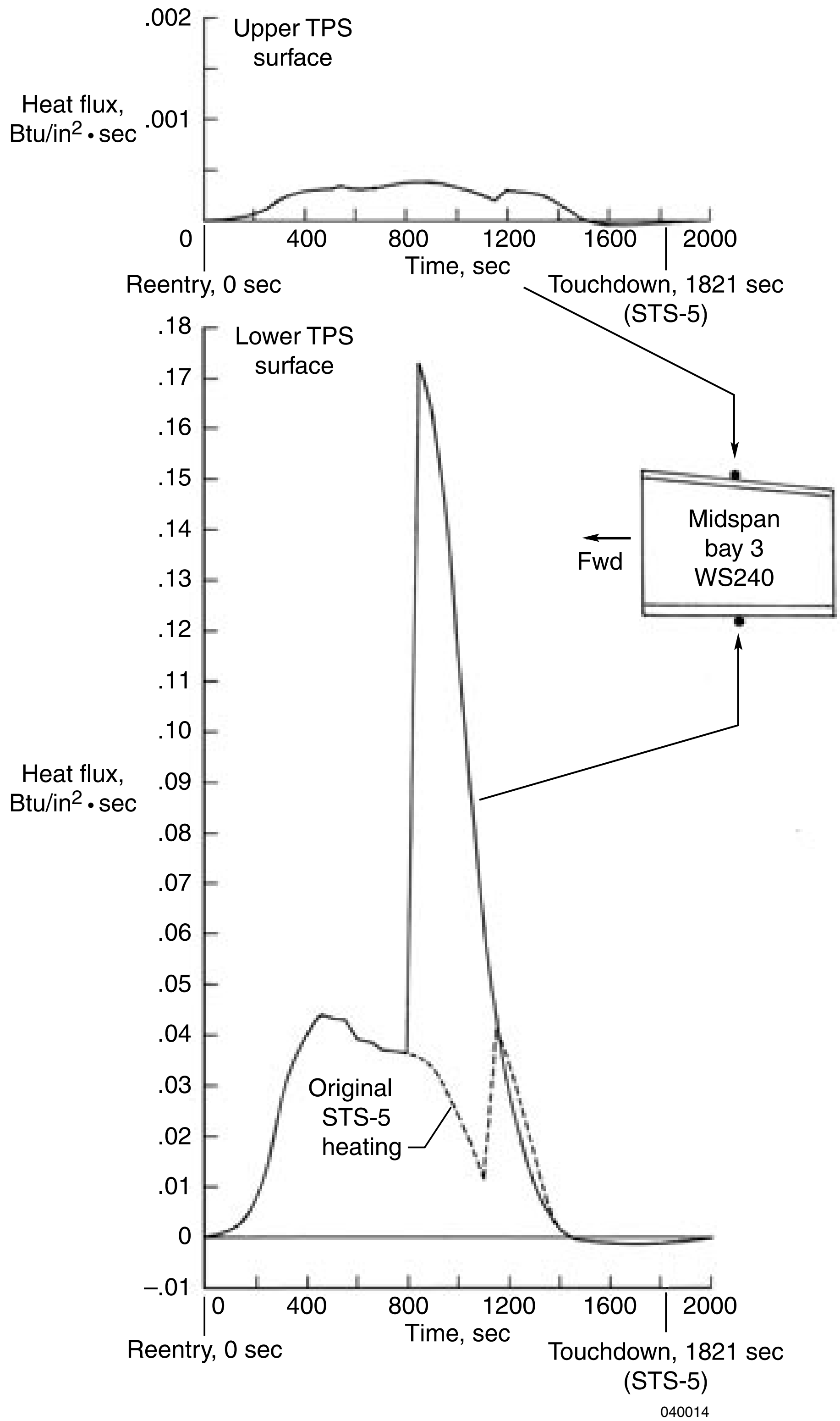
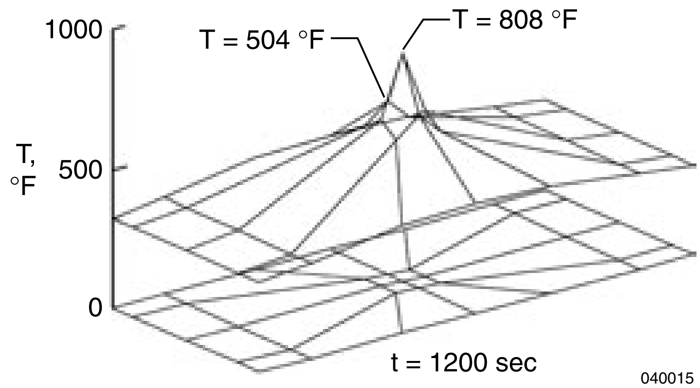
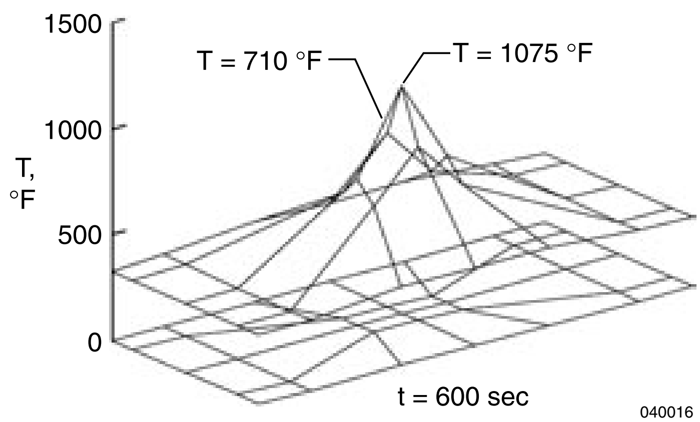


Figure 9. Modified STS-5 surface heating rates at midspan bay 3 of orbiter wing; TPS tiles missing or eroded (transition at t = 800 sec).

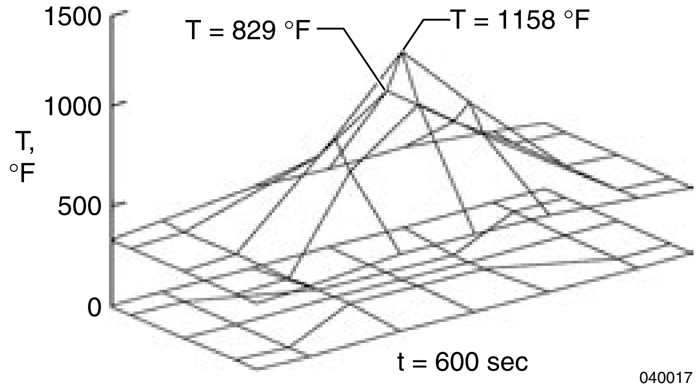


(a) One central TPS tile missing.

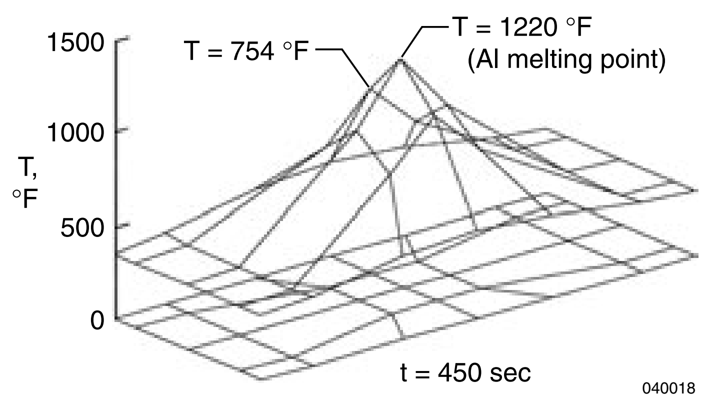


(b) Two central TPS tiles missing.

Figure 10. Windward aluminum skin temperature distributions with missing central TPS tiles; STS-5 heating (transition at t = 1100 sec).

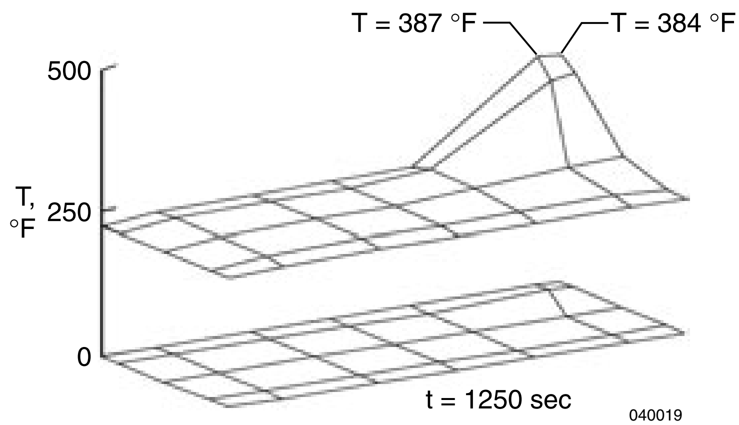


(c) Three central TPS tiles missing.

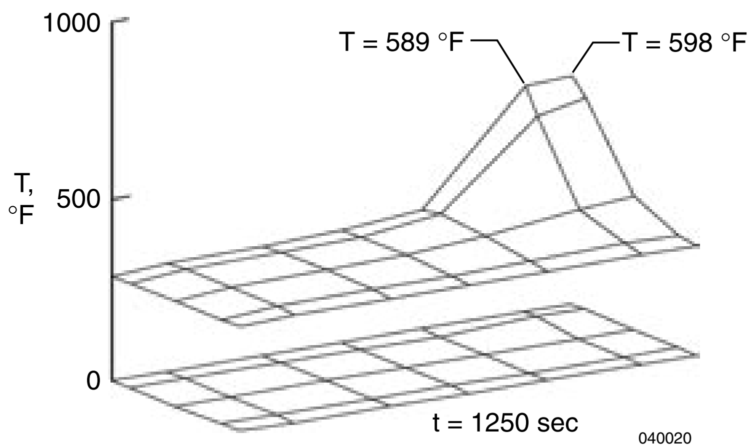


(d) Four central TPS tiles missing.

Figure 10. Concluded.

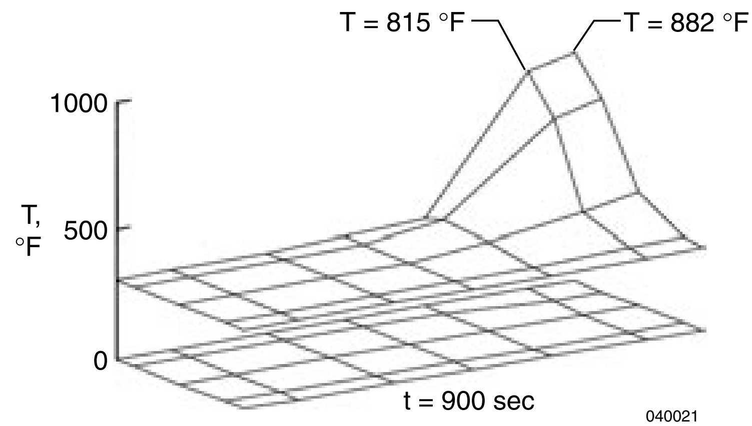


(a) One corner TPS tile missing.

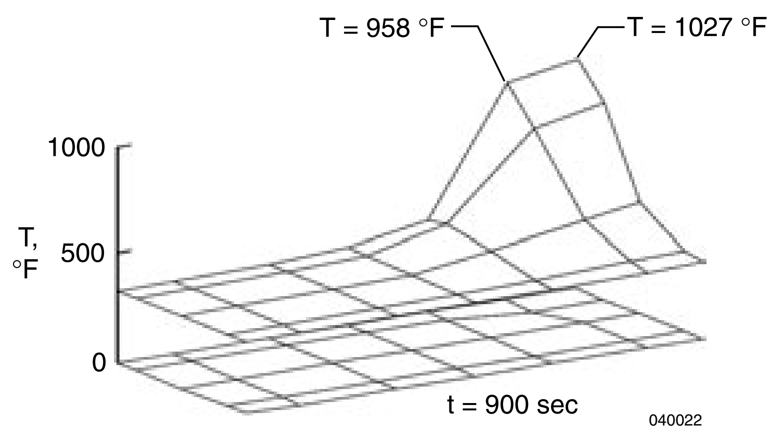


(b) Two corner TPS tiles missing.

Figure 11. Windward aluminum skin temperature distributions with missing corner TPS tiles; STS-5 heating (transition at t = 1100 sec).



(c) Three corner TPS tiles missing.



(d) Four corner TPS tiles missing.

Figure 11. Concluded.

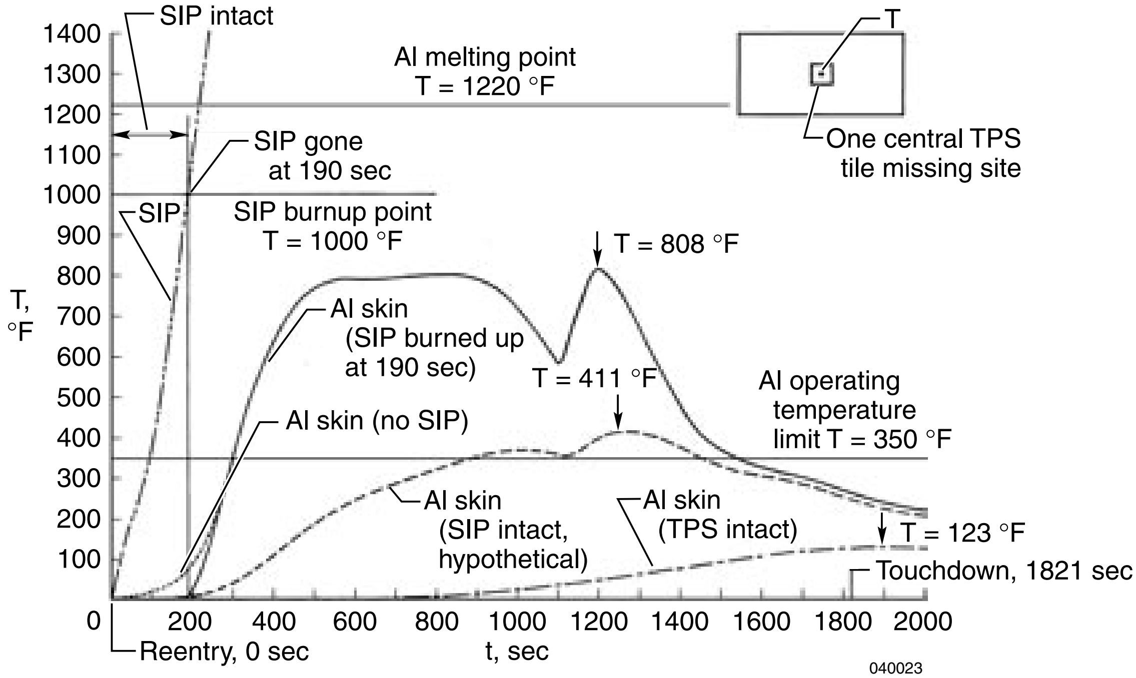


Figure 12. SIP and aluminum skin temperatures at panel center; one central TPS tile missing; STS-5 heating (transition at t = 1100 sec).

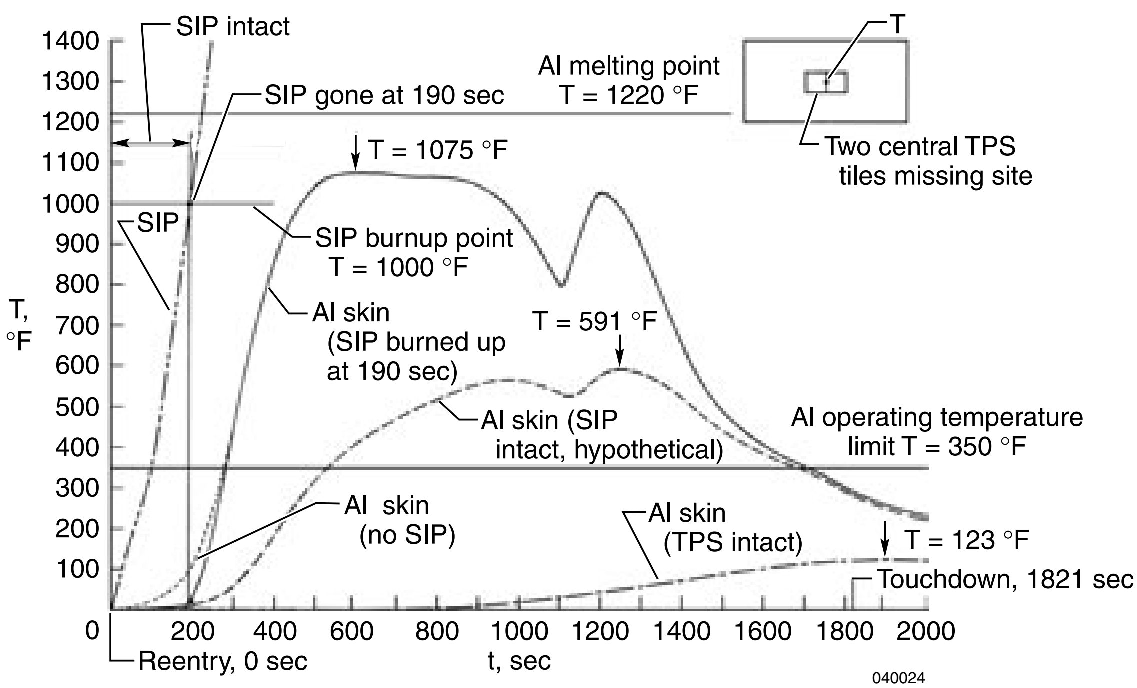


Figure 13. SIP and aluminum skin temperatures at panel center; two central TPS tiles missing; STS-5 heating (transition at t = 1100 sec).

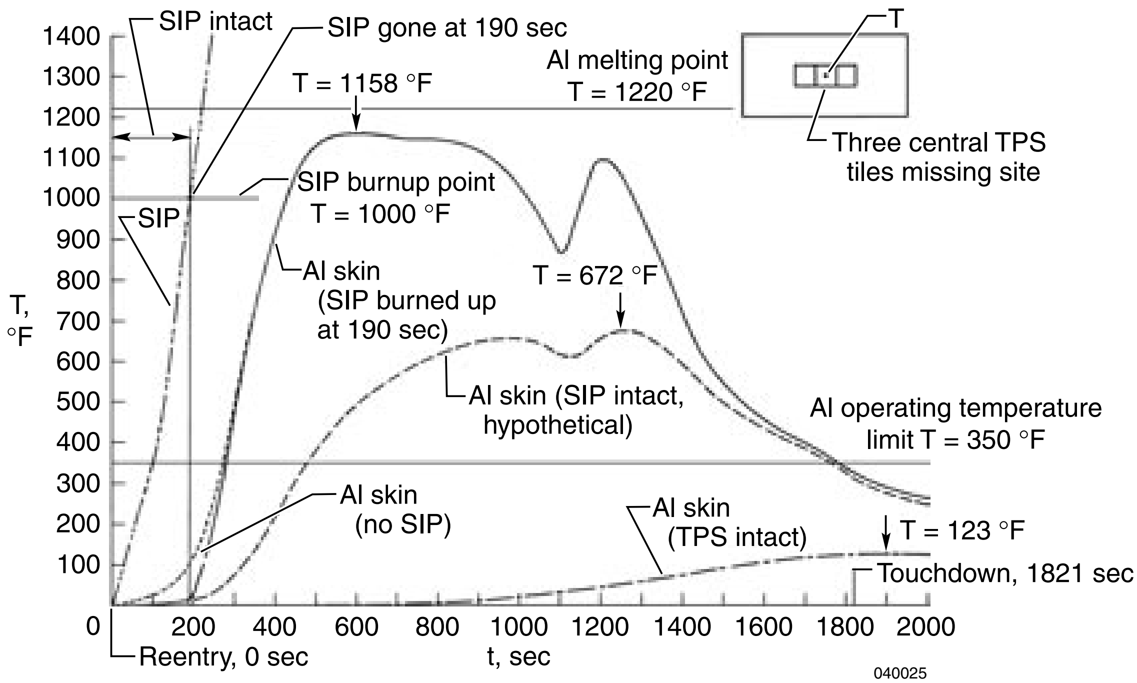


Figure 14. SIP and aluminum skin temperatures at panel center; three central TPS tiles missing; STS-5 heating (transition at t = 1100 sec).

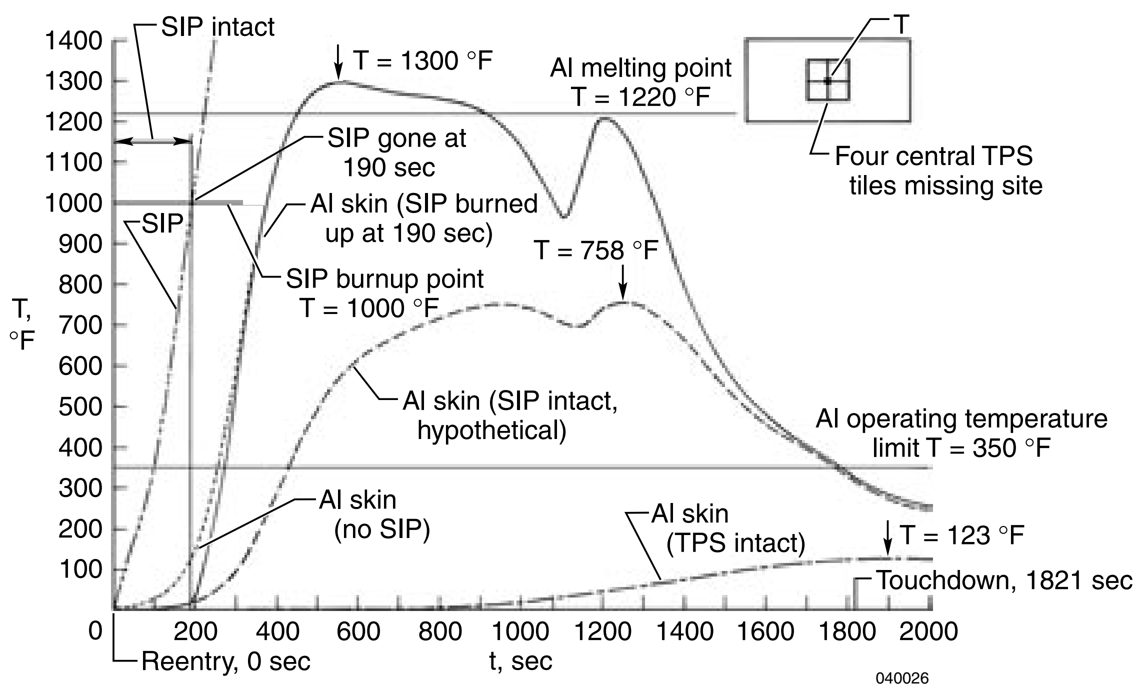


Figure 15. SIP and aluminum skin temperatures at panel center; four central TPS tiles missing; STS-5 heating (transition at t = 1100 sec).

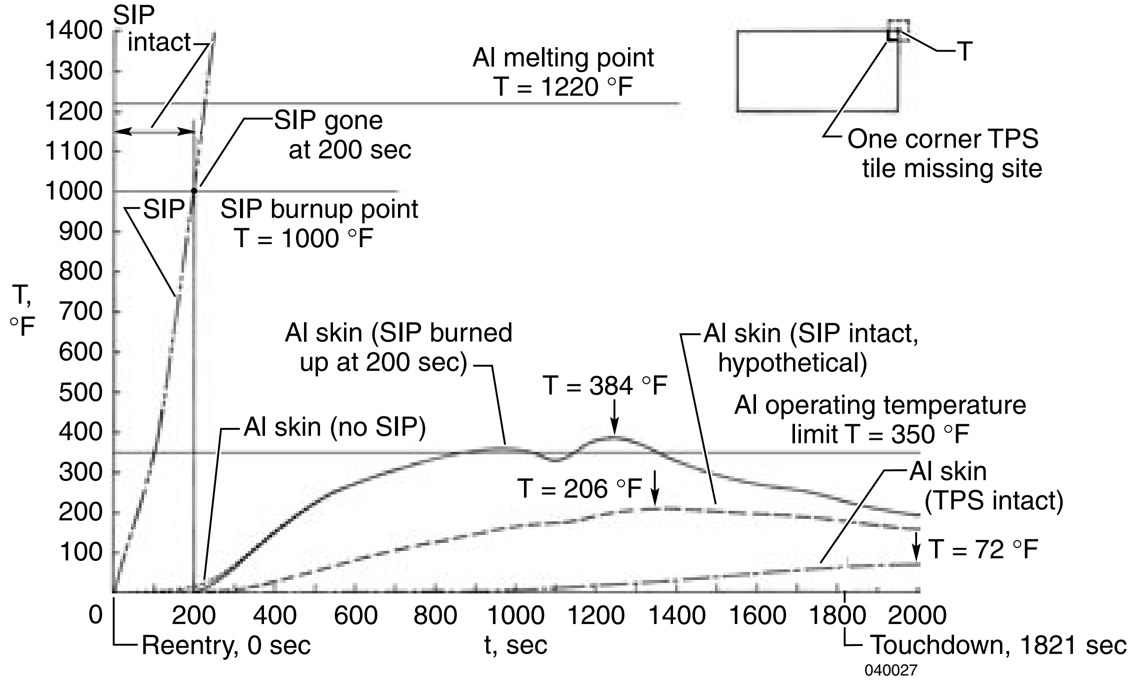


Figure 16. SIP and aluminum skin temperatures at panel corner; one corner TPS tile missing; STS-5 heating (transition at t = 1100 sec).

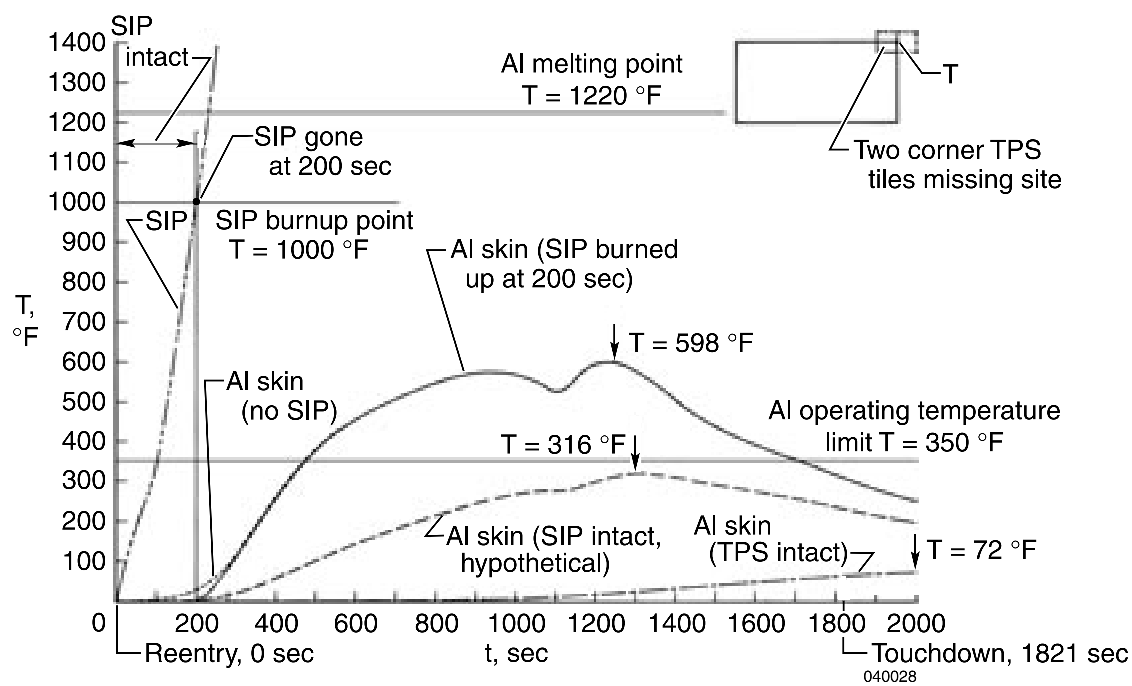


Figure 17. SIP and aluminum skin temperatures at panel corner; two corner TPS tiles missing; STS-5 heating (transition at t = 1100 sec).

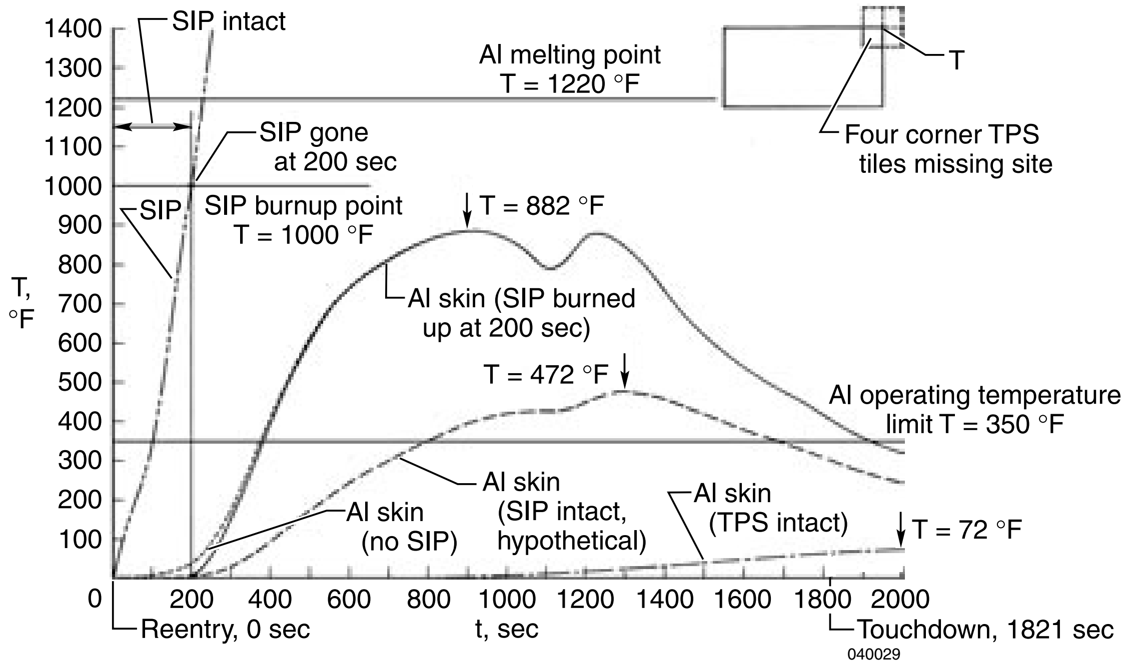


Figure 18. SIP and aluminum skin temperatures at panel corner; four corner TPS tiles missing; STS-5 heating (transition at t = 1100 sec).

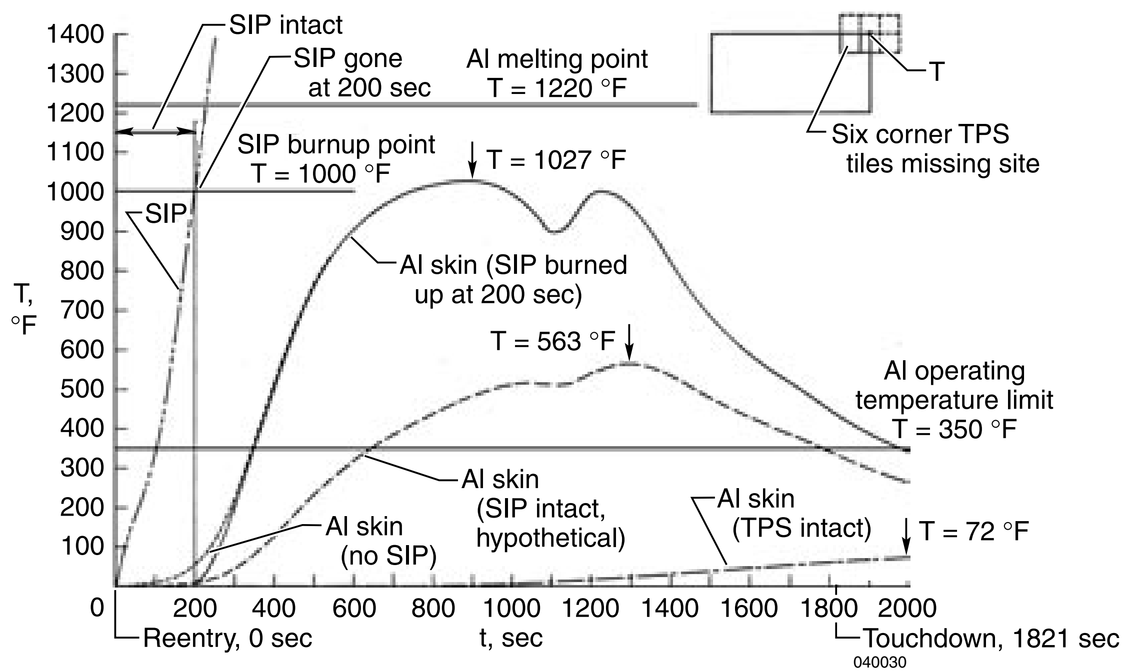


Figure 19. SIP and aluminum skin temperatures at panel corner; six corner TPS tiles missing; STS-5 heating (transition at t = 1100 sec).

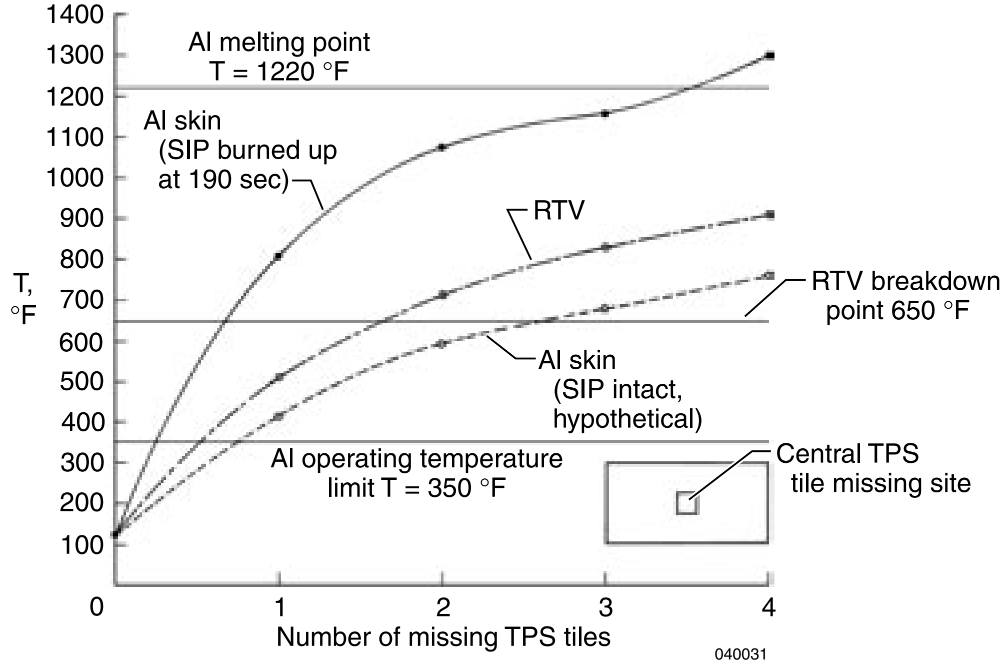


Figure 20. Aluminum skin and RTV peak temperatures as functions of number of missing central TPS tiles; STS-5 heating (transition at t = 1100 sec).

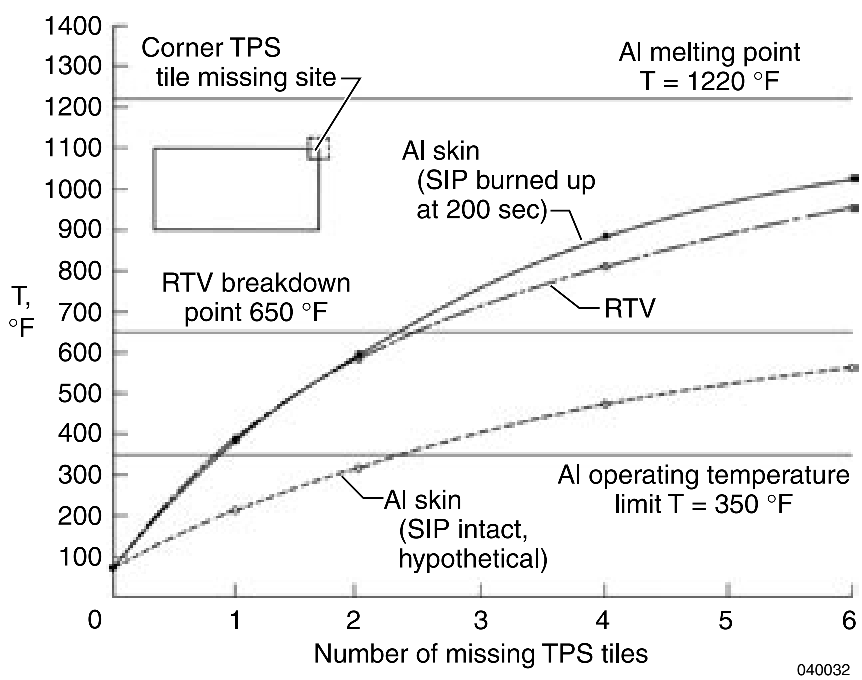


Figure 21. Aluminum skin and RTV peak temperatures as functions of number of missing corner TPS tiles; STS-5 heating (transition at t = 1100 sec).

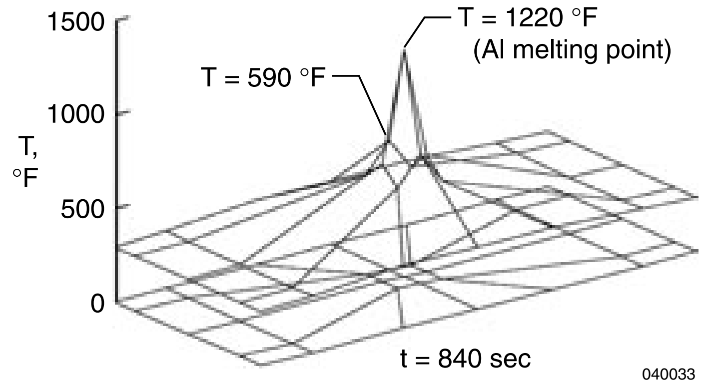
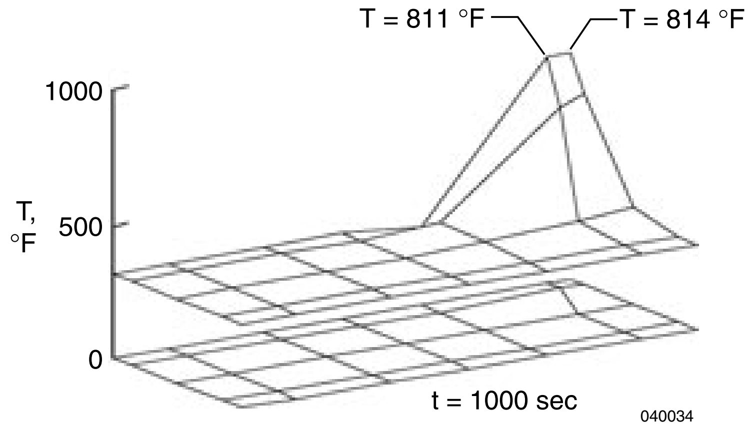
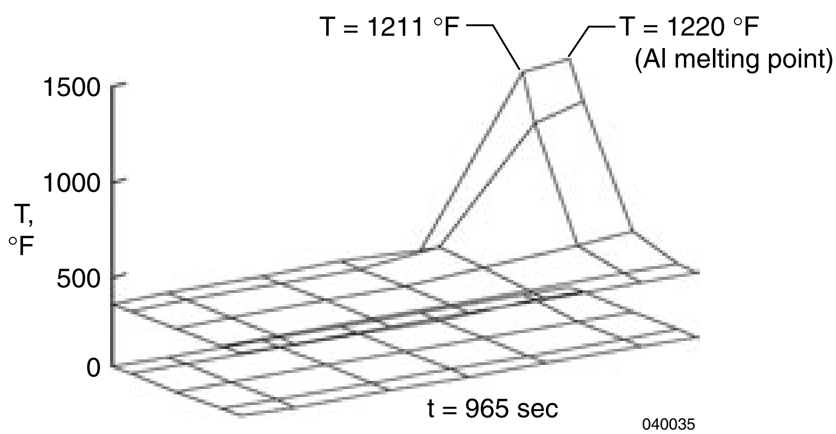


Figure 22. Windward aluminum skin temperature distributions with one missing central TPS tile (100 percent eroded, $h/h_o = 0$); modified STS-5 heating (transition at t = 800 sec).



(a) One corner TPS tile missing.



(b) Two corner TPS tiles missing.

Figure 23. Windward aluminum skin temperature distributions with missing corner TPS tiles; (100 percent eroded, $h/h_o = 0$); modified STS-5 heating (transition at t = 800 sec).

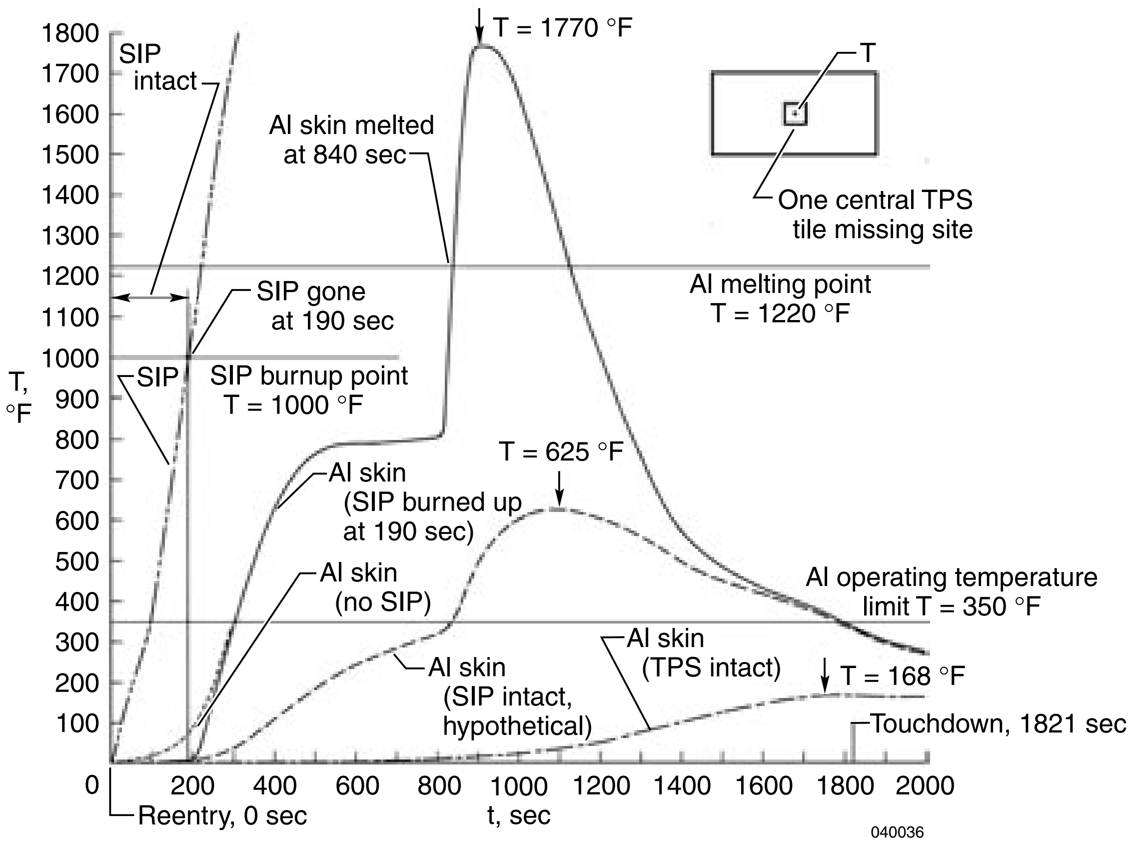


Figure 24. Windward SIP and aluminum skin temperatures at panel center; one central TPS tile missing; modified STS-5 heating (transition at t = 800 sec).

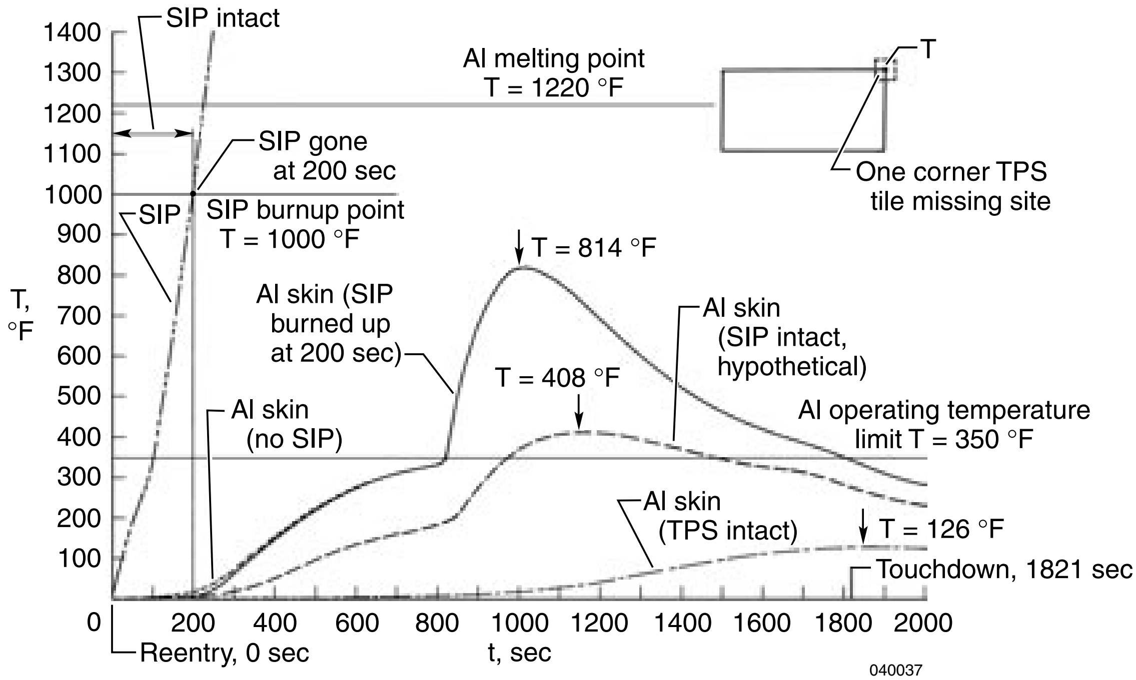


Figure 25. Windward SIP and aluminum skin temperatures at panel corner; one corner TPS tile missing; modified STS-5 heating (transition at *t* = 800 sec).

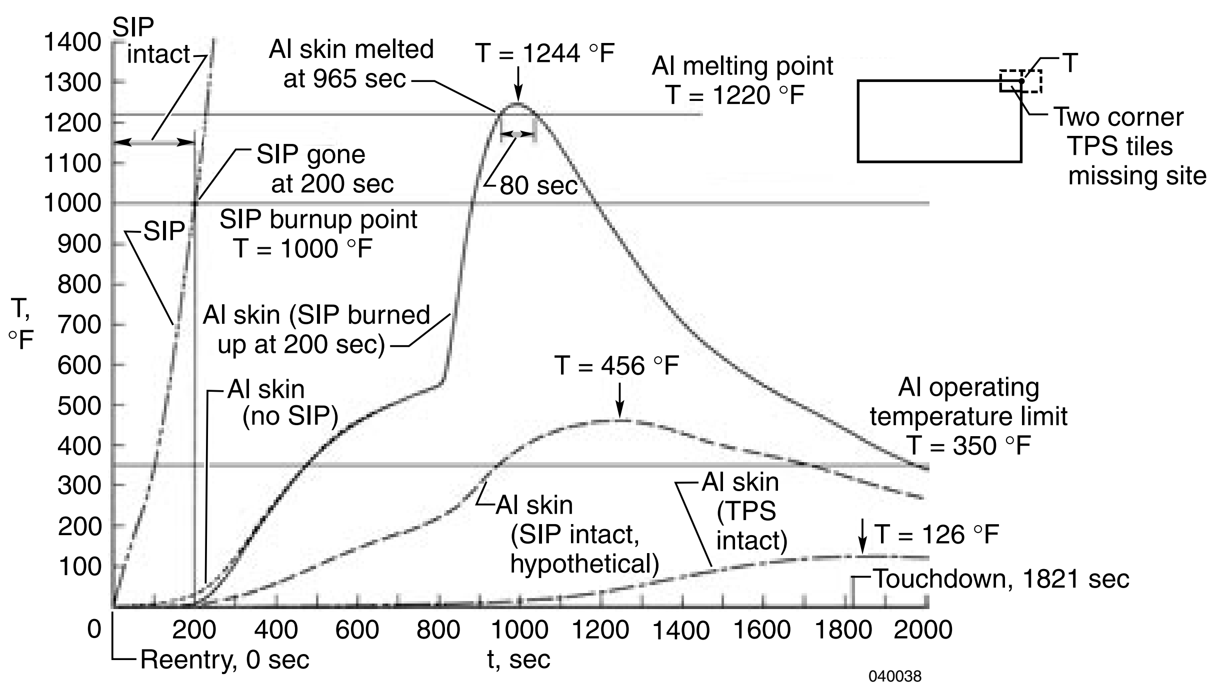


Figure 26. Windward SIP and aluminum skin temperatures at panel corner; two corner TPS tiles missing; modified STS-5 heating (transition at *t* = 800 sec).

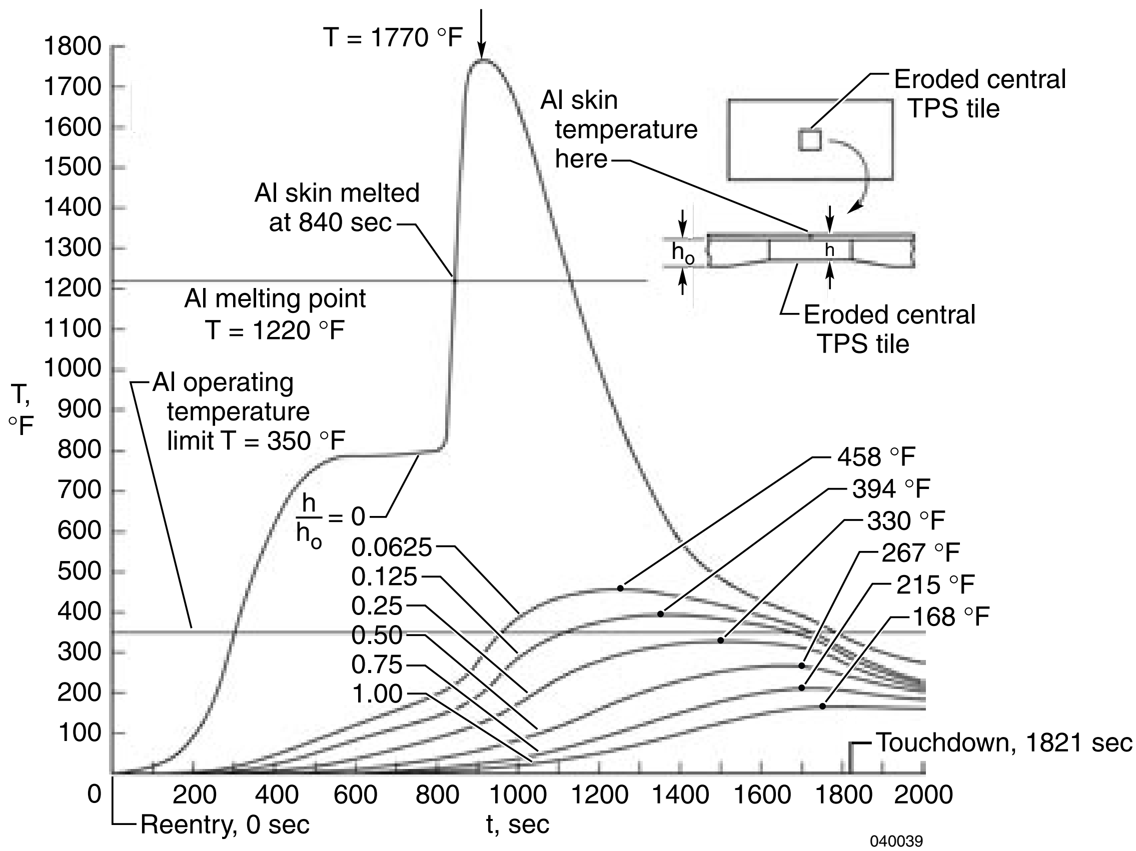


Figure 27. Variation of aluminum skin temperature with thickness of an eroded central TPS tile; modified STS-5 heating (transition at t = 800 sec).

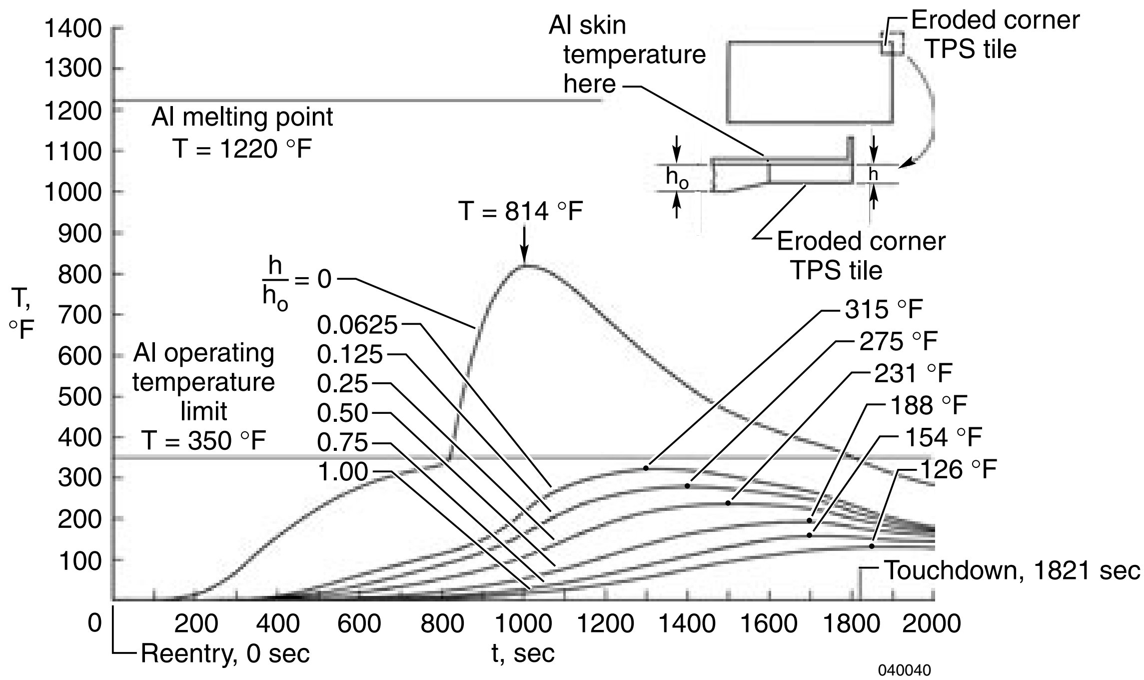


Figure 28. Variation of aluminum skin temperature with thickness of an eroded corner TPS tile; modified STS-5 heating (transition at t = 800 sec).

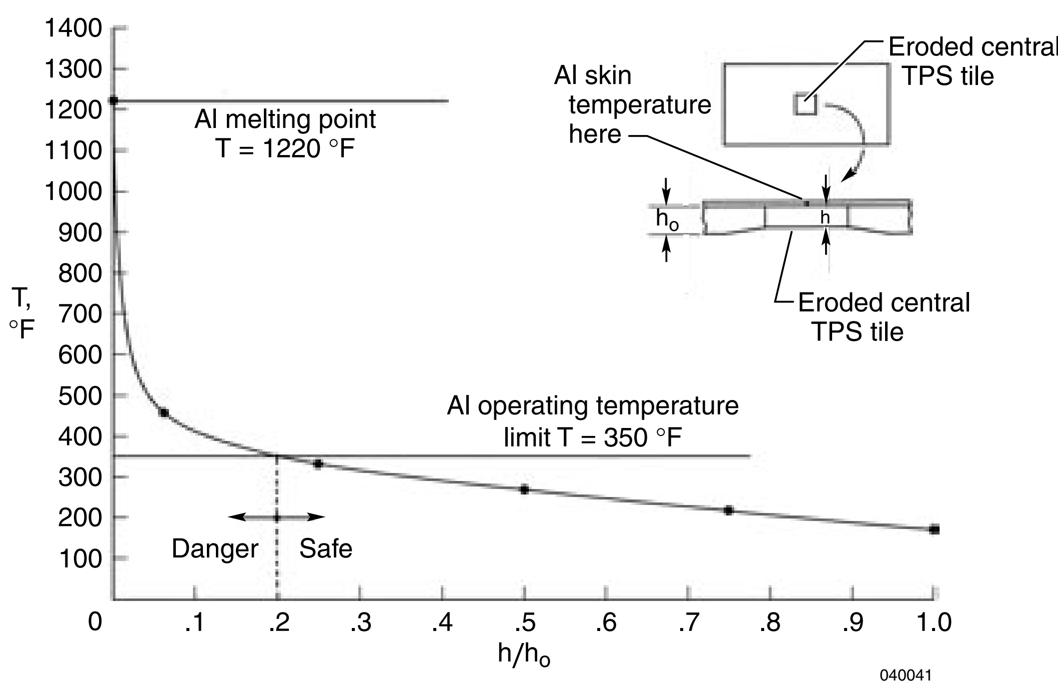


Figure 29. Time histories of aluminum skin temperatures at the site of an eroded central TPS tile; modified STS-5 heating (transition at t = 800 sec).

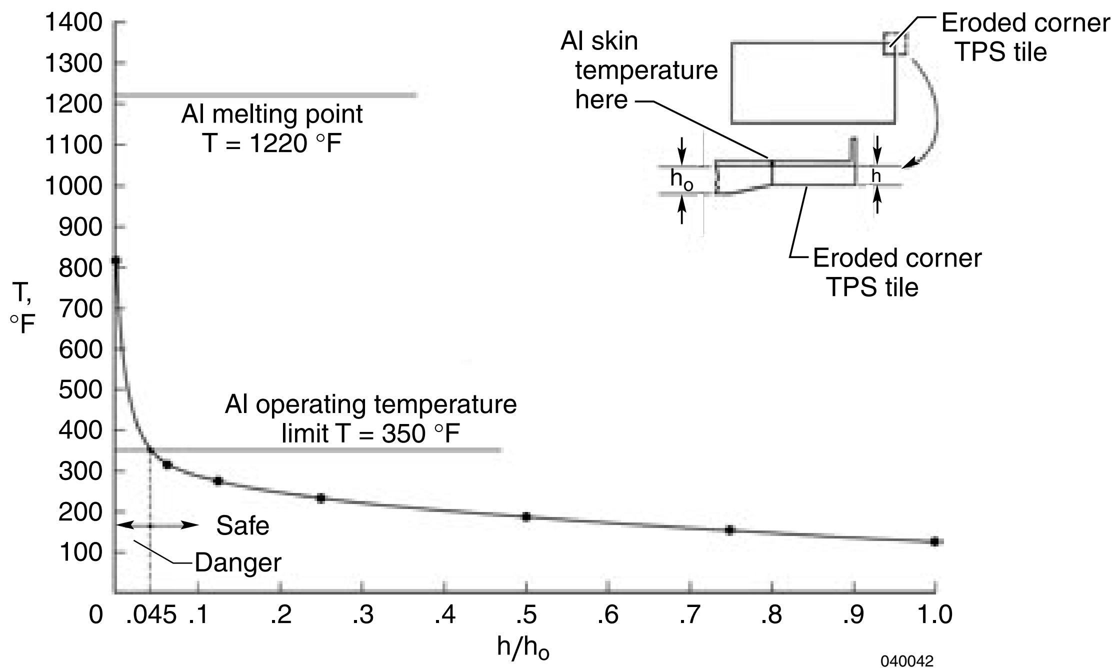


Figure 30. Time histories of aluminum skin temperatures at the site of an eroded corner TPS tile; modified STS-5 heating (transition at *t* = 800 sec).

APPENDIX

REENTRY HEATING CALCULATIONS

Figure 7 shows the original STS-5 flight trajectory of the Space Shuttle orbiter *Columbia*. This flight trajectory was used to calculate the reentry aerodynamic heating rates in the missing or eroded TPS tiles analysis. The NASA Dryden in-house computer code called TPATH (ref. 21) was used for these calculations. Various parameters for inputs to the TPATH code include: time histories of altitude, angle of attack, and Mach number (fig. 7) as well as the outer mold line geometry of the orbiter wing cross section. The program calculates transient heating rates and surface temperatures, and also computes heat transfer coefficients, boundary layer recovery temperatures, and other parameters required for the calculations of the aerodynamic heating rates. The program permits the use of different theories for calculating the heat transfer coefficients. Those theories can be properly applied at each location of interest for laminar or turbulent flow condition, or for flows with transition. Reference 14 shows that the aerodynamic heating and surface temperatures calculated by this program are in good agreement with flight measurements.

The transition criteria can be input as a function of Reynolds number and local Mach number, and/or prescribed at a specific time. In the present analysis under original STS-5 heating, the transition was prescribed at time t = 1100 sec (normal transition). This time of transition was determined by examining the measured data of STS-5. For the calculations of modified STS-5 heating, the transition time was prescribed at time t = 800 sec (premature transition) to account for the surface roughness due to missing or eroded TPS tiles.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
July 2004

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Hypothetical Reentry Thermostructural Performance of Space Shuttle Orbiter With Missing or Eroded Thermal Protection Tiles

5. FUNDING NUMBERS
WU 090-50-00-SE-RR-00-000

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Edwards, California 93523-0273

8. PERFORMING ORGANIZATION REPORT NUMBER
H-2553

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2004-212850

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 34

This report is available at the NASA Dryden Flight Research Center Web site, under Technical Reports.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report deals with hypothetical reentry thermostructural performance of the Space Shuttle orbiter with missing or eroded thermal protection system (TPS) tiles. The original STS-5 heating (normal transition at 1100 sec) and the modified STS-5 heating (premature transition at 800 sec) were used as reentry heat inputs. The TPS missing or eroded site is assumed to be located at the center or corner (spar-rib juncture) of the lower surface of wing midspan bay 3. For cases of missing TPS tiles, under the original STS-5 heating, the orbiter can afford to lose only one TPS tile at the center or two TPS tiles at the corner (spar-rib juncture) of the lower surface of wing midspan bay 3. Under modified STS-5 heating, the orbiter cannot afford to lose even one TPS tile at the center or at the corner of the lower surface of wing midspan bay 3. For cases of eroded TPS tiles, the aluminum skin temperature rises relatively slowly with the decreasing thickness of the eroded central or corner TPS tile until most of the TPS tile is eroded away, and then increases exponentially toward the missing tile case.

14. SUBJECT TERMS
Eroded TPS, Missing TPS, Reentry heat transfer, Reentry survivability, Space Shuttle orbiter

15. NUMBER OF PAGES
44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited